UNIVERSITY OF ILLINOIS
LIBRARY
AT URBANA-CHAMPAIGN
ENGINEERING

NOTICE: Return or renew all Library Materials! The *Minimum* Fee for each Lost Book is $50.00.

The person charging this material is responsible for its return to the library from which it was withdrawn on or before the **Latest Date** stamped below.

Theft, mutilation, and underlining of books are reasons for disciplinary action and may result in dismissal from the University.
To renew call Telephone Center, 333-8400

UNIVERSITY OF ILLINOIS LIBRARY AT URBANA-CHAMPAIGN

8/30/05

ENGINEERING

L161—O-1096

Digitized by the Internet Archive
in 2019 with funding from
University of Illinois Urbana-Champaign

https://archive.org/details/effectsoftaichio00rama

EFFECTS OF TAI CHI ON QUIET STANDING BALANCE AND OBSTACLE CROSSING STRATEGIES: A BIOMECHANICAL ANALYSIS

BY

ARUN KUMAR RAMACHANDRAN

B.ENGR., University of Madras, Chennai, INDIA, 2002

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Mechanical and Industrial Engineering
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2004

Urbana, Illinois

ENX 30/08/2005

Q. 6218
T04 ram

CERTIFICATE OF COMMITTEE APPROVAL

University of Illinois at Urbana-Champaign
Graduate College

December 3, 2004

We hereby recommend that the thesis by:

ARUN KUMAR RAMACHANDRAN

Entitled:

EFFECTS OF TAI CHI ON QUIET STANDING BALANCE AND OBSTACLE CROSSING STRATEGIES: A BIOMECHANICAL ANALYSIS

Be accepted in partial fulfillment of the requirements for the degree of:

Master of Science

Signatures:

Director of Research -

Head of Department -

Committee on Final Examination*

Chairperson -

Committee Member -

Committee Member -

Committee Member -

Committee Member -

Committee Member -

* Required for doctoral degree but not for master's degree

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

GRADUATE COLLEGE

This is to certify that the format and quality of presentation of the thesis submitted by

Arun Kumar Ramachandran

as one of the requirements for the degree of

Master of Science

is acceptable to the

Department of Mechanical & Industrial Engineering

Approval as of December 7, 2004

Ellen Jansen

Ellen Jansen

Departmental Format Approval

©2004 by Arun Kumar Ramachandran. All rights reserved

ABSTRACT

A cross-sectional study with experienced Tai Chi (TC) practitioners, and a longitudinal study with elderly participants involved in a TC training program were conducted with the objective of quantifying differences in quiet-standing balance, and gait during obstacle crossing due to TC experience. In the cross-sectional study, we found that when stance width was controlled to three different stance positions during quiet stance, no significant differences existed between TC practitioners and a control group for any of the balance parameters, consistent with previous studies. The most constrained stance induced significantly more postural sway especially in the medial-lateral direction. TC practitioners also used significantly greater knee flexion than control subjects, during quiet stance. Kinematic analyses performed on step-to-step gait characteristics over multiple steps during obstructed and unobstructed walking revealed that TC practitioners used a more cautious strategy by taking shorter step lengths and slower step speeds, and spent significantly longer time in single leg support on their trailing foot while stepping over an obstacle. They also appeared to place their feet closer to the obstacle both prior to and after crossing the obstacle thus producing smaller vertical clearances between the obstacle, and the leading and trailing feet. A longitudinal study with elderly subjects involved in TC training over a period of five months primarily revealed that subjects increased the vertical clearance of the leading foot over the obstacle, during the five months. No other gait parameters were found to vary significantly over the training program.

To Ray Romano
"It's all about you. Raymond."

ACKNOWLEDGEMENTS

I am eternally indebted to many people whose guidance, moral support and friendship during the course of my graduate program has helped me see the completion of this thesis. First and foremost, I express my deepest gratitude to my advisors, Elizabeth Hsiao-Wecksler and Karl Rosengren for introducing me to the world of scientific research. Their guidance and friendship proved invaluable in the discovery of my academic and research interests, and in bringing out my confidence to pursue academia to tangible proportions. I thank all my lab buddies, and Mike for their friendship, support and help during every single stage of my research. I must specially thank my roommate Rajiv for having those invaluable intellectually stimulating conversations, and for helping me discover my future interests. Thanks are also due to the members of the Locomotion Seminar for providing me with a refreshingly new intellectual atmosphere, my cricket team for providing me with the much needed sporting entertainment, and the innumerable friends I have on both sides of the hemisphere. Finally, I must confess that any word of gratitude I mention here is no indication of how supremely fortunate I am to have my parents for putting up with me for the last 23 years, and counting…

TABLE OF CONTENTS

Page

LIST OF FIGURES viii

LIST OF TABLES ix

CHAPTER 1: INTRODUCTION 1

- 1.1. Quiet-Standing Balance 1
- 1.2. Obstacle Crossing 2
- 1.3. List of References 8

CHAPTER 2: EFFECT OF TAI CHI EXPERTISE ON STANCE WIDTH AND KNEE FLEXION 11

- 2.1 Introduction 11
- 2.2 Methods 13
  - 2.2.1 Subjects 13
  - 2.2.2 Experimental Procedure 14
  - 2.2.3 Balance Measures 15
    - 2.2.3.1 Traditional Sway Analysis 15
    - 2.2.3.2 Stabilogram Diffusion Analysis 15
  - 2.2.4 Knee Flexion 16
  - 2.2.5 Statistical Analysis 16
- 2.3 Results 17
  - 2.3.1 Tai Chi Stance 17
  - 2.3.2 Balance Measures 17
    - 2.3.2.1 Traditional Sway Analysis 17
    - 2.3.2.2 Stabilogram Diffusion Analysis 17
  - 2.3.3 Knee Flexion 18
- 2.4 Discussion 18
- 2.5 Conclusion 21
- 2.6 List of References 21
- 2.7 Tables and Figures 24

CHAPTER 3: EFFECT OF TAI CHI EXPERTISE ON OBSTACLE CROSSING STRATEGY 27

- 3.1. Introduction 27
- 3.2. Methods 30
  - 3.2.1. Participants 30
  - 3.2.2. Experimental Procedure 31
  - 3.2.3. Data Analysis 32
    - 3.2.3.1. Gait Parameters 32

3.2.3.2. Obstacle-Foot Clearance Parameters 33
3.2.4. Statistical Analysis 34
3.3. Results 35
3.3.1. Gait Parameters 35
3.3.1.1. Overall Gait Speed 35
3.3.1.2. Step Lengths 35
3.3.1.3. Step Speeds 36
3.3.1.4. Step Widths 37
3.3.1.5. Time in Single Leg Support 38
3.3.2. Obstacle-Foot Clearance Parameters 38
3.3.2.1. Horizontal Clearances 38
3.3.2.2. Vertical Clearances 39
3.4. Discussion 39
3.5. Conclusion 43
3.6. List of References 44
3.7. Tables and Figures 47

CHAPTER 4: EFFECT OF TAI CHI TRAINING IN OLDER ADULTS ON OBSTACLE CROSSING STRATEGY 52
4.1. Introduction 52
4.2. Methods 54
4.2.1. Participants 54
4.2.2. Experimental Procedure 55
4.2.3. Data Analysis 56
4.2.3.1. Gait Parameters 56
4.2.3.2. Obstacle-Foot Clearance Parameters 56
4.2.4. Statistical Analysis 57
4.3. Results 57
4.3.1. Gait Parameters 57
4.3.1.1. Overall Gait Speed 58
4.3.1.2. Step Lengths 58
4.3.1.3. Step Speeds 59
4.3.1.4. Step Widths 59
4.3.1.5. Time in Single Leg Support 59
4.3.2. Obstacle-Foot Clearance Parameters 60
4.3.2.1. Horizontal Clearances 60
4.3.2.2. Vertical Clearances 60
4.4. Discussion 60
4.5. Conclusion 62
4.6. List of References 63
4.7. Tables and Figures 64

CHAPTER 5: CONCLUSIONS 69

LIST OF FIGURES

Figure Page

2.1 Feet abduction angle and stance width measured from foot traces 25
2.2 Knee flexion was calculated using motion analysis data 26
3.1 Experimental protocol 48
3.2 Five step positions used in gait parameter calculations 48
3.3a Mean overall gait speed as a function of group and obstacle height 49
3.3b Mean time spent in single leg support for the crossing step 49
3.4a Step length as a function of group and obstacle height 50
3.4b Individual step speed as a function of group and obstacle height 50
3.4c Step width as a function of group and obstacle height 50
3.5a Horizontal clearance between toe of the trailing foot at heel strike immediately prior to crossing the obstacle, and the front of the obstacle 51
3.5b Horizontal clearance between the heel of the leading foot at heel strike immediately after crossing the obstacle, and the back of the obstacle 51
3.5c Minimum vertical clearance between the trailing foot (toe or heel) and the obstacle (front or back), during the crossing step 51
3.5d Minimum vertical clearance between the leading foot (toe or heel) and the obstacle (front or back), during the crossing step 51
4.1 Five step positions used in gait parameter calculations 64
4.2a Different foot-obstacle clearances used to determine overall minimum vertical clearance for the lead (*MVCL*) and trailing foot (*MVCT*). 65
4.2b Horizontal clearances with respect to the obstacle of the lead (*HCL*) and the trailing (*HCT)* foot 65
4.3a Mean overall gait speed as a function of obstacle height and training month 66
4.3b Mean time spent in single leg support for the crossing step 66
4.4a Step length at the five measured step position as a function of training month and obstacle height 67
4.4b Individual step speed as a function of training month and obstacle height 67
4.4c Step width as a function of training month and obstacle height 67
4.5a Horizontal clearance between the heel of the lead foot and the back of the obstacle, at heel strike immediately after crossing the obstacle 68
4.5b Horizontal clearance between the toe of the trailing foot and the front of the obstacle, at heel strike immediately prior to crossing the obstacle 68
4.5c Minimum vertical clearance between the lead foot (toe or heel) and the obstacle (front or back), during the crossing step 68
4.5d Minimum vertical clearance between the trailing foot (toe or heel) and the obstacle (front or back), during the crossing step 68

LIST OF TABLES

Table Page

2.1 Statistically significant balance parameters and knee flexion by test group 24
3.1 Subject demographics and exercise behaviors (mean ± sd)..47

CHAPTER 1: INTRODUCTION

Tai Chi, or Taiji, is an ancient Chinese martial art involving slow but continuous movements and incorporates elements of strengthening, postural alignment, and concentration. It is also a fitness exercise based on combat experiences, Chinese medicine, and Chinese philosophy [34]. Recently, the potential health benefits from practicing Tai Chi have begun to receive considerable scientific attention. Some of the documented benefits include reducing blood pressure [1, 2] and stress [3, 4] to helping patients with rheumatoid arthritis [5], multiple sclerosis [6], and HIV [7]. Considerable interest has also been directed towards understanding the potential of Tai Chi as an intervention exercise aimed at improving balance [8-10] and reducing the risk of falling in the elderly [8, 11]. Anecdotal reports suggest that balance improves as a consequence of practicing Tai Chi. However, scientific findings have been inconclusive in their search for consistent trends in balance measures. As noted in a recent review [12], some studies have found significant improvements in certain balance measures, while others have found none.

1.1. Quiet-Standing Balance

Foot position can be an important determinant of standing balance and should not be left to chance [35]. Change in stance width affects one’s standing balance by increasing or decreasing the base of support. It may also affect postural sway. Lateral stability, in particular, can be highly sensitive to foot positioning [36]. In a previous study, we found that experienced TC practitioners used greater stance width than untrained individuals or even experienced dancers [33]. McIlroy and Maki [37] have suggested the need for a standardized foot position that will

allow a reasonable simulation of the postural behavior exhibited in daily life. In their study on estimating the average preferred placement of the feet during quiet stance, they proposed a stance width of 17cm and feet abduction angle of 15 degrees. Kirby et al. [35] have shown that there is significantly greater medial-lateral (ML) postural sway with feet closer together, while they reported no significant changes in ML sway for stance widths greater than 15cm. Hence, previous research has shown the effect of stance width adopted by an individual on postural sway and balance during quiet stance.

1.2. Obstacle Crossing

Falls has been reported to account for significant number of injuries in the elderly [13-15]. A major cause for falls is imbalance and tripping over obstacles during gait [14, 16-19]. Obstacle crossing in the elderly population has hence received increased attention in the scientific community. Studies have utilized biomechanical analyses to investigate and quantify age-related changes in obstacle crossing behavior [20-24]. Some of the commonly reported parameters are stride kinematics, vertical clearances between crossing foot and obstacle, horizontal foot placement prior to and after crossing the obstacle, lower extremity joint kinematics, and kinetic measures like horizontal and vertical braking impulses and forces [22, 24].

Chen and colleagues [23] conducted one of the first studies to investigate gait patterns of young and old adults in stepping over obstacles. They reported that old adults were more conservative in using slower approach and crossing speeds when crossing obstacles and their foot placement was such that they crossed the obstacle farther forward in the swing phase of the crossing cycle. However, much of their analyses were restricted to kinematics of the crossing step due to

limitations of their experimental setup. McFadyen and Winter [25] suggested the existence of anticipatory locomotor adjustments during walking in an obstructed environment, and conducted a study with the aim of observing the locomotor strategies in the kinetic profiles of muscle moments and joint power during obstructed human walking. They reported a bias in using a knee flexor strategy as opposed to a hip flexion strategy during late stance, and observed that increased ankle dorsiflexion contributed to toe clearance when crossing obstacles. Their study demonstrated the advantages and need to incorporate muscle mechanical power in assessment of locomotor strategies, in an effort to combine biomechanical with neuro-physiological analyses of the control mechanisms at the various levels of the nervous system. In an effort to map out the characteristics of obstacles that are relevant for locomotion, Patla and Rietdyk [26] investigated the kinematics of the lower extremity as it stepped over obstacles of different heights and widths. Their results revealed that limb trajectory was substantially modulated for changes in height of the obstacle, but minimally for the width, provided that the width did not force the subject to alter step length. Subjects scaled the toe clearance as a positive function of obstacle size, thus providing themselves a larger safety margin. Forward horizontal velocity of the toe, while going over the obstacle, was also reduced more than hip velocity as a function of obstacle height. However, scaling of the limb trajectory for different obstacle heights was not observed as linear functions of muscle activity or ground reaction forces. This study thus provided insight into strategies used to minimize risk of tripping or slipping as a function of visually observable properties of an obstacle. Patla and colleagues [27] also addressed the role played by expproprioceptive cues, i.e., limb posture and movement as provided by the visual system in the control of limb elevation during obstacle crossing. Their results demonstrated that limb trajectory was phase-dependent i.e. the current position and velocity states of the limb determined its

subsequent response, and that toe clearance appeared to be a complex function of the location of the obstacle and limb state. In a follow-up experiment, they found that the control of the trailing limb trajectory was not necessarily calibrated by the limb trajectory of the leading limb. Instead, their results suggested that information about the obstacle characteristics acquired through the visual system is used to control limb elevation of the leading and trailing foot independently. Higher variability in the elevation of toe over the obstacles also emphasized the role played by visual exproprioceptive inputs in controlling limb trajectories.

Chou and Draganich [28] were interested in quantifying, in young adults, what were the biomechanical differences of the trailing leg joints as obstacle height increased. They found that toe-obstacle clearance was not influenced by obstacle height. Knee flexion was found to be a more dominant than hip or ankle flexion in elevating the trailing foot. Maximum knee flexion moment during early stance, maximum knee adduction moment during late stance, and maximum ankle dorsiflexion moment during late stance were found to linearly increase with obstacle height. These results indicated the need for greater muscle strength to generate the desired moments and motion to step over obstacles compared to unobstructed walking. These results would suggest that elderly adults with decreased muscle strength would be at a disadvantage. Chou and Draganich [29] also hypothesized that horizontal placement of the trailing foot just prior to stepping over an obstacle is carefully selected by the central nervous system so as to allow enough time to flex the joints of the trailing limb, elevate the foot, and clear the obstacle. They found that reducing the toe-obstacle distance resulted in linear decreases in flexion of the trailing hip, knee, and ankle when the trailing foot crossed the obstacle. Angular velocity of hip flexion decreased whereas angular velocity of knee flexion and ankle

plantarflexion increased, which they argued was to compensate for the reduced time available to generate the required toe-obstacle clearance. Hence, they concluded that stepping over an obstacle with a shorter toe-obstacle distance required a faster response at the knee and more precise control at the hip joint of the trailing limb compared to stepping over an obstacle in a self-selected manner.

A study by Rosengren and colleagues [20] investigated the effect of physical activity level and gait related self-efficacy cognitions on kinematic variables, such as step length, step velocity, and time in single leg support. They tested fifty-five community dwelling older adults as they crossed over obstacles of increasing height. They found that, compared to active older adults, sedentary older adults adopted a more cautious walking style, exhibiting shorter step lengths and slower step velocities. Their study was the first to quantify changes in gait strategies over multiple steps during obstructed gait, wherein three steps prior to and after crossing the obstacle were analyzed. This enabled them to observe how early an obstacle disrupted the gait cycle and how long it took an individual to recover their normal gait.

Successfully navigating a cluttered environment is believed to couple visual information about objects in the environment to fundamental actions such as locomotion. Previous research has identified kinetic variables such as foot-ground reaction forces and impulses, as possible parameters of the locomotor system that are controlled by higher-order perceptual variables such as vision [30]. A strategy of interest is how ground reaction forces are regulated by advance visual information in order to increase ground clearance in stepping over obstacles of different heights. Developing on previous work investigating the kinematics of the lead and trailing foot,

and the kinetics of the lead foot in stepping over obstacles, Begg et al [31] used dual forceplates to assess the simultaneous contribution of trailing and lead foot kinetic data on understanding the process of lower limb control. Their results revealed when examining the stance phase just prior to crossing an obstacle that, compared with the lead foot, the trailing foot generated greater vertical and anterior-posterior force during push off, had lower vertical peak force during mid-stance, and produced greater vertical and anterior-posterior impulses. These kinetic modifications also resulted in increased obstacle crossing step length and reduced crossing speed as a function of obstacle height. This study thus reflected a complex interaction of braking and propulsive forces for both the lead and trailing foot when stepping over an obstacle.

Chou and colleagues [32] hypothesized that stepping over obstacles of different heights posed a greater challenge to controlling the whole body center of mass (COM), They conducted a study on six healthy young adults to investigate the effects of obstacle height on the motion of the whole body's COM and its interaction with the center of pressure (COP) of the stance foot while negotiating obstacles. A greater range of COM motion in the anterior-posterior direction, greater and faster COM motion in the vertical direction, and greater anterior-posterior distance between the COM and COP suggested the need for precise control of whole body balance to maintain dynamic stability. They suggested that aging process may cause degenerative changes in sensory systems reflecting the greater challenge to elderly people to modulate appropriate interactions between the COM and COP, which essentially puts them at a risk for tripping or falling.

The effects of an intervention program on gait mechanics associated with obstacle negotiation was studied by Lamoureux et al [24]. They argued that the kinematic and kinetic variables

obtained would provide insight into the effectiveness of a strength-training intervention and reveal the mechanisms underpinning exercise-induced changes in gait mechanics in community-dwelling older adults. From their results, they suggested that a gain in lower body strength due to the intervention led to a more effective obstacle crossing strategy, wherein subjects significantly increased their vertical heel clearance by generating greater vertical propulsive force and increased knee and ankle flexion. The authors concluded that the gain in strength allowed the subjects to adopt this safer strategy even though it was at a higher energy cost. They also observed that subjects landed farther from the obstacle after crossing with a decreased vertical descending velocity of the foot, thus providing greater control in avoiding a trip.

No previous studies have, however, explored how Tai Chi experience may influence gait behavior when the normal gait cycle is perturbed, such as when crossing an obstacle. Hence, we examined the gait behavior of experienced Tai Chi practitioners and older adults who were in a Tai Chi training intervention over multiple approach and recovery steps. It has also been reported that experienced Tai Chi practitioners use greater stance width than untrained individuals or even experienced dancers during quiet stance [33]. Quiet standing balance, which is also an integral component of Tai Chi, is also examined in Tai Chi practitioners with respect to the stance width adopted during stance. We conducted a cross-sectional with experienced Tai Chi practitioners, and a longitudinal study with elderly participants involved in a Tai Chi training program to quantify differences in gait and balance measures due to Tai Chi experience.

1.3. List of References

1. Channer, K.S., et al., *Changes in haemodynamic parameters following Tai Chi Chuan and aerobic exercise in patients recovering from acute myocardial infarction.* Postgraduate Medical Journal, 1996. **72**(848): pp. 349-351.
2. Young, D.R., et al., *The effects of aerobic exercise and T'ai Chi on blood pressure in older people: results of randomised trial.* Journal of the American Geriatrics Society, 1999. **47**(3): pp. 277-284.
3. Jin, P.T., *Efficacy of Tai Chi, brisk walking, meditation, and reading in reducing mental and emotional stress.* Journal of Psychosomatic Research, 1992. **36**(4): pp. 361-370.
4. Sandlund, E.S. and T. Norlander, *The effects of Tai Chi Chuan relaxation and exercise on stress responses and well-being: an overview of research.* International Journal of Stress Management, 2000. **7**(2): pp. 139-149.
5. Kirsteins, A.E., F. Dietz, and S.M. Hwang, *Evaluating the safety and potential use of a weight-bearing exercise, Tai-Chi Chuan, for rheumatoid arthritis patients.* American Journal of Physical Medicine and Rehabilitation, 1991. **70**(3): pp. 136-141.
6. Husted, C., L. Pham, and A. Hekking, *Improving quality of life for people with chronic conditions: the example of T'ai Chi and multiple sclerosis.* Alternative Therapies in Health and Medicine, 1999. **5**(5): pp. 70-74.
7. Howell, C.J., *The therapeutic effect of Tai Chi in the healing process of HIV.* International Journal of Alternative and Complementary Medicine, 1999. **Nov**: pp. 15-19.
8. Wolf, S.L., et al., *Reducing frailty and falls in older persons: an investigation of Tai Chi and computerized balance training.* Journal of the American Geriatrics Society, 1996. **44**: pp. 489-497.
9. Lin, Y.C., et al., *The effects of Tai Chi Chuan on postural stability in the elderly: preliminary report.* Chang Keng I Hsueh Tsa Chih, 2000. **23**(4): p. 197-204.
10. Tse, S.K. and D.M. Bailey, *T'ai chi and postural control in the well elderly.* American Journal of Occupational Therapy, 1992. **46**(4): pp. 295-300.
11. Wolf, S.L., et al., *The effect of Tai Chi Quan and computerized balance training on postural stability in older subjects.* Physical Therapy, 1997. **77**(4): pp. 371-384.
12. Wu, G., *Evaluation of the effectiveness of Tai Chi for improving balance and preventing falls in the older population--a review.* Journal of the American Geriatrics Society, 2002. **50**(4): pp. 746-754.
13. Gryfe, C.I., A. Amies, and M.J. Ashley, *A longitudinal study of falls in an elderly population, I: incidence and morbidity.* Age Ageing, 1977. **6**: pp. 201-210.
14. Prudham, D. and J.G. Evans, *Factors associated with falls in the elderly: a community study.* Age Ageing, 1981. **10**(3): pp. 141-146.
15. Tinetti, M.E., M. Speechley, and S.F. Ginter, *Risk factors for falls among elderly persons living in the community.* The New England Journal of Medicine, 1988. **319**: pp. 1701-1707.
16. Blake, A.J., et al., *Falls by elderly people at home: prevalence and associated factors.* Age Ageing, 1988. **17**: pp. 365-372.
17. Campbell, A.J., et al., *Circumstances and consequences of falls experienced by a community population 70 years and over during a prospective study.* Age Ageing, 1990. **19**(2): pp. 136-141.

18. Overstall, P.W., et al., *Falls in the elderly related to postural imbalance.* British Medical Journal, 1977. **1**: pp. 261-264.
19. Tinetti, M.E. and M. Speechley, *Prevention of falls among the elderly.* The New England Journal of Medicine, 1989. **320**: pp. 1055-1059.
20. Rosengren, K.S., E. McAuley, and S.L. Mihalko, *Gait adjustments in older adults: activity and efficacy influences.* Psychology and Aging, 1998. **13**(3): pp. 375-386.
21. McKenzie, N.C. and L.A. Brown, *Obstacle negotiation kinematics: age-dependent effects of postural threat.* Gait and Posture, 2004. **19**(3): pp. 226-234.
22. Begg, R.K. and W.A. Sparrow, *Gait characteristics of young and older individuals negotiating a raised surface: implications for the prevention of falls.* Journal of Gerontology Series A: Biological Sciences and Medical Sciences, 2000. **55**(3): pp. M147-154.
23. Chen, H.-C., et al., *Stepping over obstacles: gait patterns of healthy young and old adults.* Journal of Gerontology: Medical Sciences, 1991. **46**(6): pp. M196-M203.
24. Lamoureux, E., et al., *The effects of improved strength on obstacle negotiation in community-living older adults.* Gait and Posture, 2003. **17**(3): pp. 273-283.
25. McFadyen, B.J. and D.A. Winter, *Anticipatory locomotor adjustments during obstructed human walking.* Neuroscience Research Communications, 1991. **9**(1).
26. Patla, A.E. and S. Rietdyk, *Visual control of limb trajectory over obstacles during locomotion: effect of obstacle height and width.* Gait and Posture, 1993. **1**: pp. 45-60.
27. Patla, A.E., et al., *Locomotor patterns of the leading and the trailing limbs as solid and fragile obstacles are stepped over: some insights into the role of vision during locomotion.* Journal of Motor Behavior, 1996. **28**(1): pp. 35-47.
28. Chou, L.S. and L.F. Draganich, *Stepping over obstacles increases the motions and moments of the joints of the trailing limb in young adults.* Journal of Biomechanics, 1997. **30**(4): pp. 331-337.
29. Chou, L.S. and L.F. Draganich, *Placing the trailing foot closer to an obstacle reduces flexion of the hip, knee, and ankle to increase the risk of tripping.* Journal of Biomechanics, 1998. **31**(8): pp. 685-691.
30. Warren, W.H., Jr., D.S. Young, and D.N. Lee, *Visual control of step length during running over irregular terrain.* Journal of Experimental Psychology: Human Perception and Performance, 1986. **12**(3): pp. 259-66.
31. Begg, R.K., W.A. Sparrow, and N.D. Lythgo, *Time-domain analysis of foot-ground reaction forces in negotiating obstacles.* Gait and Posture, 1998. **7**(2): pp. 99-109.
32. Chou, L.S., et al., *Motion of the whole body's center of mass when stepping over obstacles of different heights.* Gait and Posture, 2001. **13**(1): pp. 17-26.
33. Rosengren, K.S., et al., *A comparison of balance in individuals with significant dance or Taiji experience.* Gait and Posture, in review.
34. Yang, Y., *Taijiquan: the art of nurturing, the science of power.* Zhenwu Press, Champaign, IL, in press.
35. Kirby, R.L., N.A. Price, and D.A. MacLeod, *The influence of foot position on standing balance.* Journal of Biomechanics, 1987. **20**(4): pp. 423-427.
36. Day, B.L., et al., *Effect of vision and stance width on human body motion when standing: implications for afferent control of lateral sway.* Journal of Physiology, 1993. **469**: pp. 479-99.

37. McIlroy, W.E. and B.E. Maki, *Preferred placement of the feet during quiet stance: development of a standardized foot placement for balance testing.* Clinical Biomechanics (Bristol, Avon), 1997. **12**(1): p. 66-70.

CHAPTER 2: EFFECT OF TAI CHI EXPERTISE ON STANCE WIDTH AND KNEE FLEXION

2.1. Introduction

Decreased postural stability and increased risk for falls are two of the greatest challenges associated with aging [1-5]. Tai Chi (TC), as an intervention exercise, has gained increased research interest with respect to its potential benefits of improving balance [6-8] and reducing the risk of falling in the elderly [6, 9]. TC is an ancient Chinese martial art involving slow but continuous movements and incorporates elements of strengthening, postural alignment, and concentration. Practitioners of TC anecdotally report that their balance improves as a consequence of TC; however, findings from scientific research studies are inconclusive. While some studies have found significant improvements in certain balance measures, others have found none [10].

Foot position can be an important determinant of standing balance and should not be left to chance [11]. Change in stance width affects one’s standing balance by increasing or decreasing the base of support. It may also affect postural sway. Lateral stability, in particular, can be highly sensitive to foot positioning [12]. In a previous study, we found that experienced TC practitioners used greater stance width than untrained individuals or even experienced dancers [13]. Other studies involving TC practitioners either did not control for stance width or constrained subjects to stand in specific narrow-to-moderate stance widths. Therefore, in this study, we are interested in determining whether differences in stance width may affect standing balance.

McIlroy and Maki [14] have suggested the need for a standardized foot position that will allow a reasonable simulation of the postural behavior exhibited in daily life. In their study on estimating the average preferred placement of the feet during quiet stance, they proposed a stance width of 17cm and feet abduction angle of 15 degrees. Kirby et al. [11] have shown that there is significantly greater medial-lateral (ML) postural sway with feet closer together, while they reported no significant changes in ML sway for stance widths greater than 15cm. In this study, we tested the participants in three different stance conditions – (1) average *normal stance* similar to that proposed by McIlroy and Maki [14], (2) *constrained stance* and (3) *Tai Chi stance*, a self-selected stance of the TC participants.

Research studies that have looked at the effect of foot positioning and stance width on postural sway have predominantly examined the statistical measures of Center of Pressure (COP) displacement [11, 16-18]. For example, these measures report the range of postural sway in terms of its components in the ML and anterior-posterior (AP) directions and the maximum absolute excursion of the COP from the mean value in the ML and AP directions. These parameters tend to have reasonable reliability but limited sensitivity [19-21] and do not effectively consider the dynamic properties of postural sway. Some researchers have interpreted posture as the dynamic stability of a continuously swaying body and have attempted to extract parameters which best reflect the dynamic properties of COP sway in the most sensitive way. Yamada [22] proposed a deterministic approach to characterize COP sway as a chaotic process. However, the stochastic hypothesis proposed by Collins and DeLuca [23] has been popular in recent literature for analyzing postural sway during quiet stance. They described the stochastic

properties of the COP dynamics by means of statistical mechanics properties using a two-part, random walk model.

In a more recent study by Chiari et. al. [24], the importance of controlling the foot position, which acts as the primary determinant of the base of support, was emphasized when the objective was to compare stabilometric parameters among different subjects. They found a negative correlation between the parameters quantifying postural sway in ML direction (stochastic parameters based on improved estimation techniques of SDA [21] and summary statistic scores [18]) and the base of support. However, they compared the stabilometric parameters of different subjects based on their self-selected stance, rather than comparing the stabilometric parameters of a single subject constrained to different foot positions.

Hence, in this study, we investigate the intra-subject and group based inter-subject (*TC* and *controls*) effects of stance width on postural sway during quiet stance in terms of the traditional, statistical measures and the sensitive and robust SDA parameters.

2.2. Methods

2.2.1. Subjects

We tested fifteen healthy practitioners of TC (seven females and eight males; age range: 25-66 yrs; mean age: 45.7 ± 10.6 (SD) yrs; weight: 71.61 ± 11.34 kg; height: 1.68 ± 0.05 m; mean TC experience: 6.46 ± 4.32 yrs, range: 1.5 to 15 years) and fifteen control subjects matched by age, gender and physical activity. TC practitioners were recruited from the Center for Taiji Studies, a local TC school that teaches Chen style of Taiji. The control subjects were recruited from the

University faculty and staff, and the local community. None of the subjects reported any balance and gait impairments, neuromuscular or musculoskeletal problems (e.g., joint replacement), neurological diseases (stroke, Parkinson's) or reduced visual function. The study was approved by the Institutional Review Board of the University of Illinois. Informed consent was obtained from each subject prior to their participation.

2.2.2. Experimental Procedure

Data were collected using a force plate (AMTI Force Measurement Systems, Watertown, MA; model BP600900) which measures 90cm by 60cm and is embedded in a 32 foot wooden walkway that is level with the platform. COP data were collected at a sampling frequency of 100Hz.

The assessment started with an evaluation of the subjects' exercise history. Subjects completed a questionnaire that required them to fill in the type, frequency and intensity level of their physical activities. This data was then used to determine the matching control subject based on physical activity, in addition to age and gender. Thirty trials were conducted for each subject. Trials were separated into sections of ten with each section representing a specific stance condition. Each trial was 30s in duration. The subject was given a brief rest period between trials. For all trials, the subject was made to stand on a large piece of paper taped to the top of the force platform. The subject's feet were traced on the first trial of each stance condition. The subject was instructed to maintain a quiet, upright stance with their hands comfortably positioned at their sides and eyes open, and was asked to look straight at a stationary target in the distance which was approximately at eye-level. The three stance conditions tested were: (1) *constrained stance* -

stance width of 6 cm and feet abduction angle of 20 deg, (2) average *normal stance* – stance width of 17 cm and feet abduction angle of 30 deg, (3) *Tai Chi stance* - normal comfortable stance for each TC practitioner. For the *Tai Chi stance* of control subjects, each was matched with his/her respective TC mate (*Figure 2.1*).

2.2.3. Balance Measures

Fourteen statistical parameters and eighteen stabilogram diffusion analysis parameters were computed for each stance condition.

2.2.3.1. Traditional Sway Analysis

We calculated the statistical measures of COP which are more commonly reported balance measures based on COP time series data. The computed parameters were maximum absolute excursion from the mean (*Max*), standard deviation about the mean (*SD*), range between maximum and minimum excursions (*Range*), swept area (*SweptA*), path length (*PathL*), and sway speed (*SwaySpd*). All the above parameters were reported in the anterior-posterior (AP), medial-lateral (ML) and radial (R) directions. For each trial, COP data were adjusted by subtracting the mean value of the trial for the AP and ML data.

2.2.3.2. Stabilogram Diffusion Analysis

The stabilometric parameters from SDA [23] reported in this study are short term and long term diffusion coefficients (D_S, D_L), short term and long term scaling exponents (H_S, H_L), critical time (t_c), and critical displacement (d_c) in the AP, ML and radial directions. Diffusion coefficients reflect the level of stochastic activity of the COP along the ML or AP axis or about the plane of

support [23]. Larger coefficients imply postural instability. The scaling exponents indicate the tendency of the COP to drift away from a relative equilibrium point. Typically, values above 0.5, as seen in the short-term region, imply greater drifting tendency; thus suggesting dominance of open loop control. In the long-term region, the values are typically less than 0.5, indicating a tendency to reverse the direction of drift or closed loop control. From an analytical standpoint, the critical time and displacement approximate the transition from short-term region (open loop) to the long-term region (closed loop).

2.2.4. Knee Flexion

Knee flexion was calculated using motion analysis data. Three-dimensional coordinates of the hip, knee and ankle joint centers were estimated using lower extremity motion data. Knee flexion was defined as the angle formed by the line segments connecting the above mentioned joint centers such that full extension was equal to 0° (*Figure 2.2*).

2.2.5. Statistical Analysis

Two-way repeated measures Analysis of Variance (ANOVA) were used to test for significant differences in the above mentioned balance measure parameters based on group (*TC, control*) and stance width (*Tai Chi stance*, *normal stance*, *constrained stance*). Post hoc multiple comparison tests (Tukey honestly significant difference) were performed if an ANOVA revealed a significant association. All statistical tests were performed with the SPSS statistical software package (SPSS, Inc., Chicago, IL). Based on a Bonferroni correction for multiple statistical comparisons, we regarded p values less than 0.0015 to indicate a significant association, and p values between 0.0015 and 0.05 to reflect a "borderline" association.

2.3. Results

2.3.1. Tai Chi Stance

The results show that the TC practitioners adopted a wide stance width (25cm ± 4.6) and a feet abduction angle (20° ± 3.6), when asked to take their normal comfortable stance. This supports previous studies which suggest that stance width may increase due to TC experience [13].

2.3.2. Balance Measures

No group effects were found; thus no significant differences were found between TC practitioners and controls in any of the balance parameters ($p \geq 0.047$). Therefore, results for all subjects were pooled based on stance condition (*Table 2.1*).

2.3.2.1. Traditional Sway Analysis

The 'traditional' parameters that were affected by stance width were predominantly in the ML direction. *Constrained stance* significantly increased the maximum excursion of the COP from the mean position (*Max_ML*, $p < 0.001$, 2-way ANOVA repeated measures) and consequently the standard deviation from mean (*SD_ ML*, $p < 0.001$), the range of sway (*Range_ML*, $p < 0.001$), swept area (*SweptA*, $p < 0.001$), path length (*PathL*, $p < 0.001$) and sway speed (*SwaySpd*, $p < 0.001$). The maximum excursion in the radial direction (*Max_R*, $p < 0.001$) was also found to be significantly different for the constrained stance.

2.3.2.2. Stabilogram Diffusion Analysis

In keeping with the above trend, the SDA parameters in ML and, consequently the radial direction exhibited significant differences between the *constrained stance* and the other two

stance conditions. In the ML direction, the short-term and long-term diffusion coefficients ($D_{S,ML}$ and $D_{L,ML}$, $p < 0.001$), short-term and long-term scaling exponents ($H_{S,ML}$, $p < 0.001$ and $H_{L,ML}$, $p = 0.001$) and the critical time ($t_{c,ML}$, $p < 0.001$) and displacement ($d_{c,ML}$, $p < 0.001$) were found to be significantly different in the *constrained stance* as compared with the other two stance conditions. In the radial direction, the short-term diffusion coefficient ($D_{S,R}$, $p < 0.001$), short-term scaling exponent ($H_{S,R}$, $p < 0.001$) and critical displacement ($d_{c,R}$, $p < 0.001$) were found to be significant. The long-term scaling exponent was borderline significant ($H_{L,R}$, $p = 0.009$). Three parameters in the AP direction were also found to be borderline significant: short-term diffusion coefficient ($D_{S,AP}$, $p = 0.023$), short-term scaling exponent ($H_{S,AP}$, $p = 0.007$) and the critical time ($t_{c,AP}$, $p = 0.007$)

2.3.3. Knee Flexion

Knee flexion was affected by both stance width ($p = 0.003$) and TC experience ($p = 0.02$). TC practitioners used significantly greater knee flexion than control subjects, where TC practitioners recorded a knee flexion of 15.4° during their self selected stance. When asked to take the same stance, control subjects took an average knee flexion of 12.1°. Trends indicated increasing knee flexion with stance width (*Table 2.1*).

2.4. Discussion

Individuals with Tai Chi (TC) experience were found to take a natural and comfortable stance with their feet wider as compared to the "normal" stance taken by a non-specific, general population of test subjects as reported by McIlroy and Maki [14]. Results obtained from our study suggest positive effects of having a wider stance in terms of reduced postural sway at least

in the medial-lateral direction. Wu [10] noted that duration and the style of TC practiced may affect select balance outcomes. Hence, our results suggest that future TC research is needed to determine the length of TC practice required before individuals adopt a wider stance as their comfortable and natural stance, and the influence of the TC style practiced. The practitioners in this study had TC experience of 6.46 ± 4.32 years, and practiced the Chen style of TC.

Statistically significant differences were found in the parameters based on stance width. In general, the subjects significantly tended to sway more in the ML direction when subjected to the *constrained stance*. No significant differences were observed in the parameters between the *normal stance* and the *Tai Chi stance*, though non-significant trends were noticed with increase in stance width. Kirby et al. [11] also reported no significant differences in ML postural sway with stance widths greater than 15cm. The parameters corresponding to the *Tai Chi stance* and *constrained stance* tended to have the lowest and highest values, respectively.

The stabilogram diffusion parameters can be directly related to the resultant steady-state behavior and functional interaction of the open-loop and closed-loop, or short-term and long-term neuromuscular mechanisms underlying postural control [23]. Our results indicate that a *constrained stance* typically produced significantly larger diffusion coefficients in both the short-term and long-term regions, indicating greater postural sway and hence postural instability especially in the ML direction. Kirby et. al. [11] have shown that having feet together produces significantly more medial-lateral sway in quiet stance compared with other stance widths. Possible explanations that have been offered in the past are that foot position affects the available base of support, changes the relationship of the body center of mass relative to the limits of

stability of the feet, increases passive stability of the musculoskeletal system [25], and alters the biomechanical stiffness of the musculoskeletal system [12, 26, 27].

Interestingly, the scaling exponents for the *constrained stance* condition were found to be the largest and smallest in the short-term and long-term regions, respectively, than those for the other two stance conditions. This result can be interpreted as a significantly higher drifting tendency (dominance of open loop) in the short-term region when subjects were placed in the *constrained stance* condition, and, dominance of closed loop control over the long-term region.

Our results show that the transition from open-loop to closed-loop control, as indicated by the critical time and displacement, is delayed for the *constrained stance* condition, thus allowing for greater postural sway.

Among the significant traditional parameters, the maximum excursion of COP from the mean (*Max)*, the standard deviation (*SD*) and the range of sway (*Range*) are direct indicators of directional postural sway. The ML sway contributed significantly to sway in the radial direction. The result was an increase in overall sway as indicated by the swept area and path length. The subjects also tended to sway faster when their stance was constrained, as indicated by sway speed.

As noted in the results, non-significant trends were observed in the parameters with the *Tai Chi stance* and the *constrained stance* conditions producing the lowest values and highest values, respectively. Even though the *Tai Chi stance* and the *normal stance* did not elicit statistically

significantly different responses, the trend in the data suggests decreasing postural sway with increasing stance width.

2.5. Conclusions

TC practitioners adopted a wide stance width when asked to take their normal comfortable stance. No significant differences were found in postural sway response between the TC practitioners and the control subjects, which was in support of previous findings. The major results obtained from this study showed that postural sway significantly increased, especially in the ML direction, when stance width was constrained. Non-significant trends in our results suggested that postural sway decreases with increasing stance width. Hence, the phrase "wider is better" appears to also apply to human balance; thus greater stability in everyday life may be achieved by increasing one's stance width during stance and locomotion. Further research should examine interventions such as Tai Chi that involve adopting a wider stance as one's normal comfortable stance.

2.6. List of References

1. Tromp, A.M., et al., *Predictors for falls and fractures in the longitudinal aging study Amsterdam.* Journal of Bone and Mineral Research, 1998. **13**(12): pp. 1932-1939.
2. O'Loughlin, J.L., et al., *Incidence of and risk factors for falls and injurious falls among the community-dwelling elderly.* American Journal of Epidemiology, 1993. **137**(3): pp. 342-354.
3. Tinetti, M.E., M. Speechley, and S.F. Ginter, *Risk factors for falls among elderly persons living in the community.* The New England Journal of Medicine, 1988. **319**: pp. 1701-1707.
4. Campbell, A.J., et al., *Circumstances and consequences of falls experienced by a community population 70 years and over during a prospective study.* Age Ageing, 1990. **19**(2): pp. 136-41.
5. Sattin, R.W., *Falls among older persons - a public health perspective.* Annual Review of Public Health, 1992. **13**: pp. 489-508.

6. Wolf, S.L., et al., *Reducing frailty and falls in older persons: an investigation of Tai Chi and computerized balance training.* Journal of the American Geriatrics Society, 1996. **44**: pp. 489-497.
7. Lin, Y.C., et al., *The effects of Tai Chi Chuan on postural stability in the elderly: preliminary report.* Chang Keng I Hsueh Tsa Chih, 2000. **23**(4): pp. 197-204.
8. Tse, S.K. and D.M. Bailey, *T'ai chi and postural control in the well elderly.* American Journal of Occupational Therapy, 1992. **46**(4): pp. 295-300.
9. Wolf, S.L., et al., *The effect of Tai Chi Quan and computerized balance training on postural stability in older subjects.* Physical Therapy, 1997. **77**(4): pp. 371-384.
10. Wu, G., *Evaluation of the effectiveness of Tai Chi for improving balance and preventing falls in the older population--a review.* Journal of the American Geriatrics Society, 2002. **50**(4): pp. 746-754.
11. Kirby, R.L., N.A. Price, and D.A. MacLeod, *The influence of foot position on standing balance.* Journal of Biomechanics, 1987. **20**(4): pp. 423-7.
12. Day, B.L., et al., *Effect of vision and stance width on human body motion when standing: implications for afferent control of lateral sway.* Journal of Physiology, 1993. **469**: pp. 479-499.
13. Rosengren, K.S., et al., *A comparison of balance in individuals with significant dance or Taiji experience.* Gait and Posture, in review.
14. McIlroy, W.E. and B.E. Maki, *Preferred placement of the feet during quiet stance: development of a standardized foot placement for balance testing.* Clinical Biomechanics (Bristol, Avon), 1997. **12**(1): pp. 66-70.
16. Diener, H.C., et al., *Quantification of postural sway in normals and patients with cerebellar diseases.* Electroencephalography and Clinical Neurophysiology, 1984. **57**: pp. 134-142.
17. Hasan, S.S., M.J. Lichtenstein, and R.G. Shiavi, *Effect of loss of balance on biomechanics platform measures of sway: influence of stance and a method for adjustment.* Journal of Biomechanics, 1990. **23**(8): pp. 783-789.
18. Prieto, T.E., et al., *Measures of postural steadiness: differences between healthy young and elderly adults.* IEEE Transactions on Biomedical Engineering, 1996. **43**(9): pp. 956-966.
19. Baloh, R.W., et al., *A prospective study of posturography in normal older people.* Journal of the American Geriatrics Society, 1998. **46**(4): pp. 438-443.
20. Collins, J.J., et al., *Age-related changes in open-loop and closed-loop postural control mechanisms.* Experimental Brain Research, 1995. **104**(3): pp. 480-492.
21. Chiari, L., et al., *An improved technique for the extraction of stochastic parameters from stabilograms.* Gait and Posture, 2000. **12**(3): pp. 225-234.
22. Yamada, N., *Chaotic swaying of the upright posture.* Human Movement Science, 1995. **14**: pp. 711-726.
23. Collins, J.J. and C.J. De Luca, *Open-loop and closed-loop control of posture: a random-walk analysis of center-of-pressure trajectories.* Experimental Brain Research, 1993. **95**(2): pp. 308-318.
24. Chiari, L., L. Rocchi, and A. Cappello, *Stabilometric parameters are affected by anthropometry and foot placement.* Clinical Biomechanics (Bristol, Avon), 2002. **17**(9-10): pp. 666-677.

25. Henry, S.M., J. Fung, and F.B. Horak, *Effect of stance width on multidirectional postural responses.* Journal of Neurophysiology, 2001. **85**(2): pp. 559-570.
26. Winter, D.A., Prince, F., Frank, J.S., Powell, C., and Zabek, K.F., *Unified theory regarding A/P and M/L balance in quiet stance.* Journal of Neurophysiology, 1996. **75**(6): pp. 2334-2343.
27. Winter, D.A., et al., *Stiffness control of balance in quiet standing.* Journal of Neurophysiology, 1998. **80**(3): pp. 1211-1221.

2.7. Tables and Figures

Table 2.1. Statistically significant balance parameters and knee flexion by test group. Results for all subjects combined. Constrained stance parameters were significantly different from TC and normal stance. There were no significant differences between TC and normal stance.

- p values obtained from 2-way ANOVA repeated measures
- $p < 0.001$ denotes statistical significance

Description	**Mean ± SD**		
	Tai Chi stance	***Normal stance***	***Constrained stance***
Stance width (cm)	25 ± 4.6	17	6
Abduction (°)	20 ± 3.6	30	20
SDA $D_{S,ML}$	2.0 ± 1.0	2.2 ± 1.2	9.5 ± 4.8
$D_{L,ML}$	0.16 ± 0.2	0.2 ± 0.2	0.85 ± 0.7
$D_{R,ML}$	11.8 ± 5.2	12.1 ± 6.8	20.7 ± 9.0
$H_{S,ML}$	0.7 ± 0.05	0.7 ± 0.04	0.8 ± 0.04
$t_{c,ML}$ (sec)	0.9 ± 0.1	1.0 ± 0.1	1.3 ± 0.4
$d_{c,ML}$ (mm)	1.9 ± 1.2	3.0 ± 1.8	20.1 ± 12.9
$d_{c,R}$ (mm)	20.5 ± 15.3	22.0 ± 12.9	37.7 ± 21.3
$H_{S,R}$	0.7 ± 0.04	0.7 ± 0.0	0.81 ± 0.0
TRAD ML_Max (mm)	4 ± 1	4 ± 1	10 ± 3
ML_SD (mm)	1 ± 0	1 ± 0	3 ± 1
ML_Range (mm)	7 ± 2	8 ± 2	18 ± 5
SweptA (mm2)	728 ± 232	760 ± 282	1070 ± 281
SwaySpd (mm/sec)	19 ± 2	19 ± 2	20 ± 2
R_Max (mm)	12 ± 3	12 ± 3	14 ± 2
PathL (mm)	575 ± 80	574 ± 84	613 ± 80
Knee Flexion			
TaiChi subjects (°)	15.4 ± 4.1	16.5 ± 3.9	16.6 ± 3.9
Control subjects (°)	12.1 ± 4.0	12.5 ± 4.1	12.7 ± 4.3

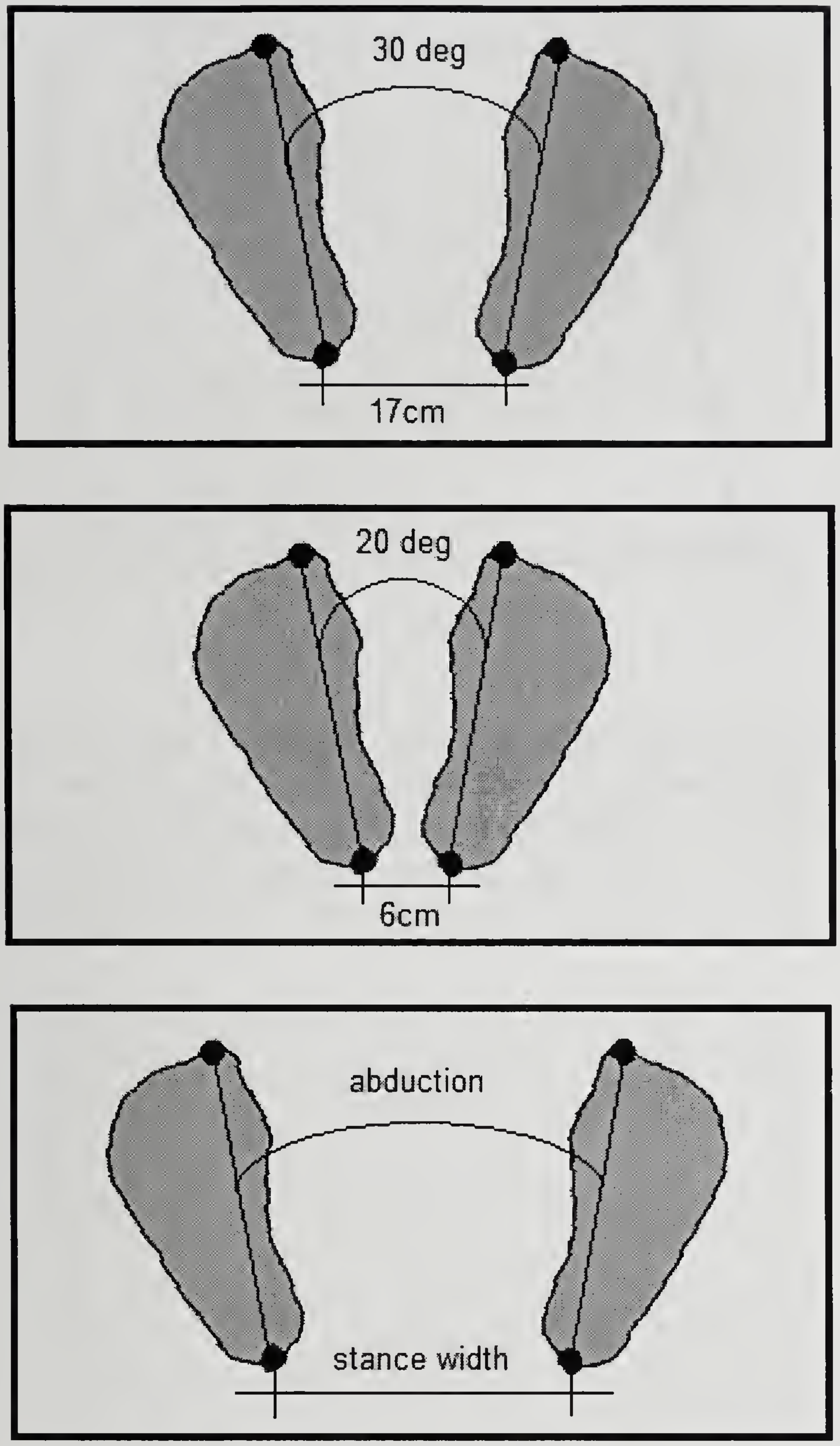

Figure 2.1. Feet abduction angle and stance width measured from foot traces. Stance width is defined as the distance between the mid-points of each heel in the medio-lateral direction. Feet abduction is defined as the angle enclosed by the lines joining the mid-point of each heel to the tip of the large toe on each foot. Tai Chi stance defined the self-selected comfortable stance of the Tai Chi practitioners and the Normal stance was defined as the average stance width, consistent with literature [3]. Control subjects matched their respective Tai Chi mate in each of the three stance conditions. Postural sway (center of pressure) data were collected for 30 seconds per trial (10 trials in each stance condition) from a force platform (AMTI, 100 Hz sampling frequency.

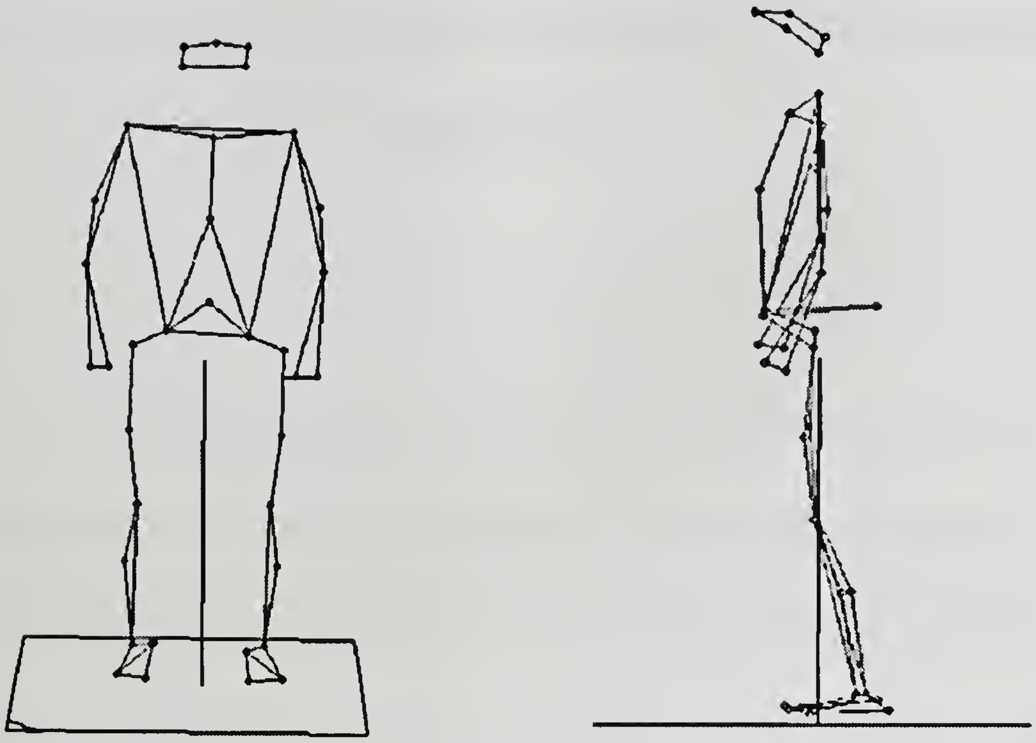

Figure 2.2. Knee flexion was calculated using motion analysis data. Three-dimensional coordinates of the hip, knee and ankle joint centers were estimated using lower extremity motion data. Knee flexion was defined as the angle formed by the line segments connecting the above mentioned joint centers such that full extension was equal to 0°.

CHAPTER 3: EFFECT OF TAI CHI EXPERTISE ON OBSTACLE CROSSING STRATEGY

3.1. Introduction

Tai Chi (or *Taiji*, in current Chinese pinyin) is an ancient Chinese martial art and fitness exercise based on combat experiences, Chinese medicine, and Chinese philosophy [1]. The actual origin of this art is unclear, but it has developed into a form of exercise that is practiced by millions of individuals in China. More recently, the interest in Tai Chi has extended beyond China. Within the last twenty years, Tai Chi and its potential health benefits have begun to receive considerable attention by the Western scientific and medical communities. These potential benefits range from reducing blood pressure [2, 3] and stress [4, 5] to helping patients with rheumatoid arthritis [6], multiple sclerosis [7], and HIV [8].

Because of its appeal as a slow and non-strenuous exercise that is conducive to group interaction, Tai Chi has been promoted to older adults as an intervention to improve physical and mental fitness [9-11], improve cardio-respiratory function [12], and prevent falls [13]. In a seminal study, Wolf and colleagues found that healthy older adults who practiced Tai Chi for 15 weeks delayed the onset of falls by 47.5% when compared to individuals that received either computerized balance training or a wellness education program [14]. More recently, Wolf et al. [15] and Nowalk et al. [16] conducted randomized control tests on less robust older adults that were living in congregate living or long-term care facilities. Neither study found statistically significant differences between groups; however, both studies did note trends in fall reduction due to Tai Chi experience. Tai Chi training emphasizes enhanced attention when moving through

a given environment and enhanced awareness of one's balance limitations [1]. It is possible that this training may cause Tai Chi practitioners to modify their movement strategies and move more cautiously through their surroundings, which may provide some explanation for these observed reductions in falls.

Previous Tai Chi studies have focused predominately on gait speed, either directly or indirectly via the time to walk a given distance or the distance walked in a given time. The results of these studies have been mixed, with some studies finding that gait speed increases with Tai Chi experience [7, 17], while others found no change or trends indicating that gait speed decreases [14-16, 18]. Only one study to date has examined other gait parameters. Mak and Ng [17] found that, in addition to using faster gait speeds, older Tai Chi practitioners appear to use longer stride lengths and similar cadences when compared to active older non-practitioners. It is not known whether Tai Chi experience modifies other gait parameters such as step width and single leg support time.

From previous studies, it appears that Tai Chi experience may cause modifications in stance width and single leg support time during upright stance. Rosengren et al. [19] found that individuals with Tai Chi experience may utilize a larger base of support since they preferred larger stance widths when standing in a normal upright position as compared to normal controls and experienced dancers. Tai Chi training also involves extended periods in single leg stance. As a consequence, numerous studies have examined single leg stance times during upright stance [20-25]. These studies suggest that single leg stance time increases with Tai Chi experience

given sufficient training exposure. It is not known whether these behaviors will translate into larger step widths or longer periods in single leg stance while walking.

Fall risk is also associated with the ability to accommodate external perturbations or challenging balance situations. Destabilizing activities like negotiating obstacles or raised surfaces has been shown to account for nearly 50% of falls in community–dwelling older adults [26]. Previous studies have mostly examined gait under normal walking conditions. Tse and Bailey [20] and Ross et al. [22] used a more challenging gait task, where they assessed the ability to walk in tandem (heel to toe) along a straight line. These studies simply collected the number of consecutive steps taken [20] or time to walk a given distance along a line [22]. Other studies have used biomechanical analyses to investigate obstacle crossing behavior in healthy adults. While most investigators primarily reported the kinematic characteristics like crossing speed, crossing foot clearance, horizontal foot placement prior to and after crossing the obstacle, lower extremity joint angles, and stride parameters like stride lengths, widths and speeds [27, 28], a few studies have also looked at the kinetic properties like the peak braking and propulsive forces in the vertical and anterior-posterior directions [28, 29]. All these studies have shown that gait and obstacle crossing parameters may vary as a function of age, physical activity level, obstacle height, and step position relative to the obstacle. However, most of these studies have focused on the crossing step and steps immediately prior to and after crossing the obstacle. Rosengren et al. [19] in their study on 55 community-dwelling older adults showed that an obstacle produces changes in gait at least three steps prior to, and after crossing the obstacle. Hence, they were able to examine how early an obstacle perturbed the gait cycle, and more importantly how long it took the individuals to recover to their normal gait.

No previous studies have explored how Tai Chi experience may influence gait behavior when the normal gait cycle is perturbed, such as when crossing an obstacle. Hence, in this study we examine the gait behavior of experienced TC practitioners over multiple approach and recovery steps. We hypothesized that Tai Chi practitioners move more cautiously through their surroundings by using movement strategies, which may result in reduced fall risk. To test this hypothesis, we conducted a cross-sectional study with long-term Tai Chi practitioners and age, sex, and physical activity matched control subjects. Biomechanical gait characteristics were measured when walking on a level surface or over a fixed obstacle of varying height. Gait parameters of gait speed, single leg stance time, step length, step width, step speed, and vertical and horizontal obstacle clearance were examined for effect of Tai Chi experience, obstacle height, and step position relative to the obstacle.

3.2. Methods

3.2.1. Participants

Fifteen healthy practitioners of Tai Chi and fifteen control subjects matched by age, sex and physical activity level were tested in this study (*Table 3.1*). All Tai Chi practitioners were students at a local Tai Chi school that teaches Chen style, and were selected by their Tai Chi master (Y.Y.) for study participation since they demonstrated a high level of proficiency in their Tai Chi training. The Tai Chi group had an average of 6.5 ± 4.4 (S.D.) years (range 1.5 to 15 years) of Tai Chi training. Control subjects were recruited from university personnel and the local community. No subjects reported any balance and gait impairments, neuromuscular or musculoskeletal problems (e.g., joint replacement), neurological diseases (stroke, Parkinson's), or reduced visual function. The study was approved by the Institutional Review Board of the

University of Illinois. Informed consent was obtained from each subject prior to participation. In order to determine overall physical activity level, subjects were given a short questionnaire to assess their exercise habits. The questionnaire required input on (1) the average number of days per week with exercise bouts of 30 minutes or more in the previous six months, (2) the average exercise intensity, and (3) description of physical activities other than Tai Chi such as walking, biking, running, etc. The level of intensity was assessed using a 4-point Likert Scale (1 = easy, 2 = moderate, 3 = somewhat hard, and 4 = hard). In addition, Tai Chi practitioners reported the frequency of their Tai Chi practice, i.e., number of hours per week. See Table 1 for summary statistics.

3.2.2. Experimental Procedure

Subjects were instructed to walk barefoot at a self-selected pace along a 9.8 m elevated (0.11 m high × 1.8 m wide) walkway (*Figure 3.1*). Three conditions were tested: no obstacle (*00*), 10 cm obstacle (*10*), and 40 cm obstacle (*40*). Conditions were presented in order of increasing obstacle height. Obstacle heights were chosen based on previous research [30]. The 10 cm obstacle was designed to be similar to step and curb heights, and the 40 cm obstacle was designed to be moderately challenging but well within the range of the subjects' ability to walk over. Both obstacles were 10 cm in depth and 113 cm in length.

Kinematic data were collected using a 6-camera optical motion capture system (Vicon Motion Systems, Oxford, UK; Datastation 460) that was sampled at 100 Hz and then filtered using a recursive 4th order Butterworth low-pass filter with a cut-off frequency of 6 Hz. Thirty-six markers were attached to the subject; however only data from markers placed at the left and right

calcaneous (heel), 1^{st} metatarsal heads (toe), and sacrum were used in this study. Markers were also placed on the top four corners of the obstacle. Kinematic data were collected for the central 3.5 m of the walkway, which spanned the capture volume of the camera set-up.

For each test condition, the subject was allowed a minimum of two practice trials to familiarize him/herself with the walking surface and the gait task, and then three data trials were recorded. Ground reaction force data were collected from a large force plate that was embedded halfway down the walkway. (Data are not reported in this study.) During obstacle crossing trials, the obstacle was place over the distant portion of the force plate (*Figure 3.1*). Only trials with a single clean foot strike within the force plate surface were recorded. Subjects were blinded to this requirement.

3.2.3. Data Analysis

For each trial, we examined five consecutive steps: two "approach" steps, one "crossing" step, and two "recovery" steps, which were defined at heel strike (*Figure 3.2*). We used these five steps since we were able to consistently measure at least these five steps within our capture volume for all subjects. The crossing step for the no-obstacle trials was determined from placement of the feet relative to the standard location of the obstacle in obstacle crossing conditions.

3.2.3.1. Gait Parameters

For each of the five step positions, the following gait parameters were computed for each trial (*Figure 3.2*): anterior-posterior step length (SL), medial-lateral step width (SW), and average

step speed between consecutive steps (SS). The time in single leg support (SLST) while crossing the obstacle was defined as the time duration that the trailing limb was in single leg support, i.e., from the instant of toe-off to heel strike of the lead foot (first foot over the obstacle) while it crossed over the obstacle. Average walking speed (*gait speed*) was estimated over a distance of 3.5m and based on temporal data for the sacral marker.

3.2.3.2. Obstacle-Foot Clearance Parameters

Vertical and horizontal clearance values were calculated between the foot and obstacle for both the lead and trailing feet during obstacle crossing trials. We shall refer to the approach side of the obstacle as the obstacle "front" and the recovery side as the obstacle "back". For all calculations, the location of the front or back of the obstacle was determined from the average vertical and horizontal positions of the two reflective markers on the respective side. The minimum vertical clearance for the lead (*MVCL*) or trailing (*MVCT*) foot was defined as the minimum of four measurements based on when the heel or toe marker was vertically above the front or back top edge of the obstacle. The horizontal clearance between the obstacle front side and the toe marker on the trailing foot (*HCT*) was calculated at the instant of heel strike of the trailing foot during the crossing step (*Figure 3.2*). Similarly, the horizontal clearance between the obstacle back side and the heel marker on the lead foot (*HCL*) was calculated at the instant of heel strike of the lead foot immediately after crossing the obstacle. For each test condition, average values from the three trials are reported for each gait parameter.

3.2.4. Statistical Analysis

Mixed multivariate analysis of variance (MANOVA) , 2 (group: TC, controls) × 2 (gender: male, female) × 3 (obstacle height: 0, 10, 40) were performed to examine the effects of group, gender, and obstacle height on the step length, step speed, step width, overall gait speed, and time in single leg support during obstacle crossing. Obstacle height was chosen as a repeated measure variable, and group and gender were selected as between-subject factors.

To assess how gait parameters (step length, speed, and width) were affected by step position relative to each obstacle, 2 (group: TC, controls) × 2 (gender: male, female) × 5 (step position: second approach, first approach, crossing, first recovery, second recovery) MANOVA were conducted for each obstacle condition. In these analyses, step position was the repeated measure, and group and gender were between-subject factors.

To assess the foot-obstacle clearance data, 2 (group: TC, controls) × 2 (gender: male, female) × 2 (obstacle height: 10, 40) MANOVA were performed on minimum vertical clearances of the leading (MVCL) and trailing (MVCT) foot during obstacle crossing, and the horizontal clearances in the approach (HCT) and recovery (HCL) directions.

Independent samples t-tests were run on the population demographics to identify any differences between the subjects in the two groups. (*Table 3.1*)

Significant differences and interactions were verified using Tukey HSD post-hoc comparisons. Based on a Bonferroni correction for multiple statistical comparisons, we regarded p values less

than 0.003 to indicate a significant association, and p values between 0.003 and 0.0016 to reflect a “borderline” association. All statistical analyses were run on SPSS v12 (SPSS Inc., Chicago, IL).

3.3. Results

3.3.1. Gait Parameters

3.3.1.1. Overall Gait Speed

Figure 3.3a displays the gait speed as a function of obstacle height and group. Overall, the TC practitioners ($M = 0.99$ *m/s*, $SE = 0.03$) walked significantly slower than the control subjects ($M = 1.16$ *m/s*, $SE = 0.03$), $p < 0.001$. There was also a significant main effect of obstacle height on gait speed, $p < 0.001$. Post hoc analyses revealed that the subjects significantly decreased their walking speeds with increase in obstacle height ($M = 1.16$ *m/s*, $SE = 0.03$, *00*; $M = 1.11$ *m/s*, $SE = 0.02$, *10*; $M = 0.96$ *m/s*, $SE = 0.02$, *40*). No significant gender effects were obtained, $p = 0.339$.

3.3.1.2. Step Lengths

Figure 3.4a displays the average step lengths taken by the two groups as a function of step position and obstacle height. The TC practitioners ($M = 599$ *mm*, $SE = 19$, *A2*; $M = 593$ *mm*, $SE = 14$, *A1*; $M = 642$ *mm*, $SE = 14$, *C*; $M = 638$ *mm*, $SE = 14$, *R1*; $M = 621$ *mm*, $SE = 13$, *R2*) took significantly shorter step lengths than the controls ($M = 670$ *mm*, $SE = 19$, *A2*; $M = 670$ *mm*, $SE = 14$, *A1*; $M = 699$ *mm*, $SE = 14$, *C*; $M = 684$ *mm*, $SE = 14$, *R1*; $M = 669$ *mm*, $SE = 13$, *R2*) during each of the five steps analyzed, $p<0.024$. A significant interaction between obstacle

height and group also revealed that TC practitioners had shorter approach steps, over all three obstacle conditions. Gender did not have any significant effect on step lengths, $p > 0.293$. Obstacle height had a significant main effect on the five step lengths, $p<0.002$. From Figure 3.4a, it can be inferred that subjects significantly reduced their second approach step for the 40cm obstacle compared to the 10cm obstacle and no obstacle conditions. The first approach step produced significant differences between all three conditions, with significant reductions in the step lengths for the 10cm and 40cm obstacle conditions. The step length for the 40cm obstacle was, once again, smaller than the 10cm obstacle. However, crossing step length was greater for the 10cm obstacle compared to the 40cm obstacle, with the corresponding step during normal walking shorter than both obstacle conditions. The smaller crossing step for the 40cm obstacle can be attributed to the result that the subjects placed their lead foot significantly closer to the tallest obstacle i.e. 40cm after crossing it $(M = 221.5mm, SE = 11.2, 10; M = 180.2mm, SE = 9.6, 40), p < 0.001$. Recovery step lengths typically increased with an increase in obstacle height. Both groups took a longer recovery step immediately after crossing the obstacle, which was significantly greater for the 40cm obstacle condition compared to the other two conditions, as verified by post-hoc comparisons. Subjects displayed smaller second recovery step lengths, but the means for the 10cm and 40cm obstacle conditions were still greater than that for normal walking, suggesting the need for at least one more step before the effect of the perturbation in gait got nullified.

3.3.1.3. Step Speeds

Figure 3.4b plots the step speeds of the two groups as a function of step position and obstacle height. Step speeds were found to be significantly different between the TC practitioners and the

control subjects, for each of the step positions analyzed, $p < 0.001$, with the TC practitioners taking slower steps. An interaction between obstacle height and group also revealed that TC practitioners ($M = 1.014$ *m/s*, $SE = 0.032$) took a significantly slower final approach step before crossing the obstacle than the controls ($M = 1.215$ *m/s*, $SE = 0.032$), $p = 0.008$.

From figure 3.4b, it can be seen that the participants maintained a relatively constant step speed during normal walking, $p = 0.698$, but made significant alterations to their step speeds for the two obstacle conditions, $p < 0.001$. The subjects significantly reduced their crossing speeds during perturbed walking, and then recovered with a gradual increase in their recovery step speeds. Obstacle height had a borderline significant main effect on the step speeds for all the steps, $p < 0.023$. Post hoc comparisons showed that speeds for the 40cm obstacle condition were different from normal walking during each of the five steps analyzed.

3.3.1.4. Step Widths

The average step widths during gait are plotted in Figure 3.4c as a function of step position and obstacle height, for the two groups. Data suggested that during normal walking, the TC practitioners took wider steps ($M = 92.39$ *mm*, $SE = 5.72$) than the control subjects ($M = 80.49$ *mm*, $SE = 5.72$), though this result was not significant, $p = 0.153$. Also during normal walking, step widths over the five different steps did not vary significantly, $p = 0.118$. Obstacle height also had a significant main effect on the step widths immediately before, and after crossing the obstacle, $p < 0.001$. Post hoc analyses revealed that the first approach step width was significantly smaller for the 10cm and 40cm obstacles when compared to normal walking. However, step widths were greater than normal walking on the first recovery step, with the 40cm obstacle producing a significantly wider recovery step compared to the other two conditions.

Gender also had a significant main effect on the step widths. Male subjects took significantly wider steps than females during the first approach ($M = 90.64$ *mm*, $SE = 6.02$, *Male*; $M = 66.6$ *mm*, $SE = 6.43$, *Female*), crossing ($M = 94.9$ *mm*, $SE = 5.83$, *Male*; $M = 70.12$ *mm*, $SE = 6.24$, *Female*), and first recovery ($M = 109.55$ *mm*, $SE = 6.39$, *Male*; $M = 90.32$ *mm*, $SE = 6.83$, *Female*) step widths, $p < 0.011$.

3.3.1.5. Time in Single Leg Support

TC practitioners spent significantly longer times in single leg support during obstacle crossing than the control subjects ($M = 0.692$ *sec*, $SE = 0.013$, *TC*; $M = 0.617$ *sec*, $SE = 0.013$, *Controls*), $p < 0.001$, such that SLS time increased with obstacle height. Post hoc comparisons for a significant obstacle height and group interaction, $p < 0.001$, also revealed that the TC practitioners recorded greater single leg support times for both obstacle conditions, while there was no difference between the groups during normal walking (*Figure 3.3b*).

3.3.2. Obstacle-Foot Clearance Parameters

3.3.2.1. Horizontal Clearances

No significant group differences were found for the horizontal clearances between the trailing foot and obstacle front (HCT), and the lead foot and obstacle back (HCL), $p > 0.094$. From Figure 3.5a, TC practitioners appeared to place their trailing foot closer to the front of the obstacle before crossing it, during both the 10cm ($M = 180.5$ *mm*, $SE = 12.3$, *TC*; $M = 210.1$ *mm*, $SE = 12.3$, *C*) and 40cm ($M = 194.9$ *mm*, $SE = 14.3$, *TC*; $M = 225.1$ *mm*, $SE = 14.3$, *C*) obstacle conditions. Obstacle height had a significant main effect on the horizontal clearance for the lead foot, $p < 0.001$ (Figure 3.5b). In general, subjects placed their lead foot farther away

from the obstacle after crossing the 10cm obstacle *(M = 221.5mm, SE = 11.2)*, than when crossing the 40cm obstacle *(M = 180.2mm, SE = 9.6)*.

3.3.2.2. Vertical Clearances

No significant group differences were found for the minimum vertical clearance between the obstacle and either the trailing (MVCT) or lead foot (MCVL) (Figures 3.5c and 3.5d). However, the TC practitioners tended to have smaller vertical clearances for both feet. Obstacle height also had a significant effect on the clearances, $p < 0.012$, such that vertical clearance was significantly greater for the 40cm obstacle, for both the trailing foot *(M = 144.8 mm, SE = 6.3, 10; M = 199.8 mm, SE = 9.2, 40)* and the lead foot *(M = 105.6 mm, SE = 4.6, 10; M = 124.3 mm, SE = 5.7, 40)*. Gender had a significant main effect on the vertical clearance for the trailing foot. Female subjects *(M = 155.6 mm, SE = 8.65)* recorded a smaller clearance than male subjects *(M = 189.11 mm, SE = 8.09)*, $p = 0.009$.

3.4. Discussion

More recently, Wolf et al. [15] and Nowalk et al. [16] conducted randomized control tests on less robust older adults that were living in congregate living or long-term care facilities. Neither study found statistically significant differences between groups; however, both studies did note trends in fall reduction due to Tai Chi experience. Wolf et al. [15] found that the Tai Chi group, which received training for 48 weeks, reduced their risk for falls by 25% when compared to a wellness education control group. Nowalk et al. [16] found that the group receiving both Tai Chi training and fear of falling behavioral training had a rate of falling of 58%, whereas a strength-

training exercise group had a rate of 72%, and a wellness education control group had a rate of 75%.

These results support our hypothesis that Tai Chi experience may alter gait behavior, especially when crossing obstacles. Tai Chi training emphasizes an awareness of one's surrounding environment and balance limitations. Consequently, Tai Chi practitioners may use more cautious strategies when challenged by perturbations to normal gait. The overall gait speed, and individual step speeds clearly show that the TC practitioners opted for a slower gait than their age and activity matched control subjects. The speeds, being self-selected, are more a reflection of the strategy adopted by the two groups, rather than being indicative of the physical capabilities of the subjects. Significant differences in step speeds were observed between normal walking and the most challenging obstacle condition during each of the five steps analyzed. This suggests that adjustments to perturbed gait occur at least two steps prior to crossing the obstacle, and persists up to at least two steps after crossing the obstacle, which is consistent with findings of Rosengren [30].

However, the result that TC practitioners spent longer times in single leg support during obstacle crossing suggests a behavior that is not necessarily cautious. It has been reported previously that longer times in single leg support decreases stability in older adults [31, 32], suggesting that TC practitioners are at a greater risk of losing their stability while crossing the obstacle. However, it must be noted that longer single leg support time during obstacle crossing is an inevitable consequence of slower crossing speed. In addition, it could be a natural extension of extended periods of practice standing on a single leg by the TC practitioners, as we had hypothesized.

The cautious or potentially conservative strategies of the TC practitioners were also displayed in their step lengths during the gait trials. The TC practitioners recorded significantly shorter steps during each of the five steps analyzed. Interestingly, this behavior was evident even during normal, unobstructed walking. It should also be noted that TC practitioners took significantly shorter steps during their approach, for the 10cm and 40cm obstacle conditions. Due to the nature of the data capture volume in our laboratory setting, the steps labeled as the second and first approach reflect the steps immediately prior to obstacle crossing, rather than being the first two steps taken during the trial. Hence, we are unable to comment on the level of preparatory strategies on the part of the subjects. However, it allows us to observe the kind of modifications that the two groups make, in tune with their strategies, immediately prior to crossing the obstacle.

The position of the trailing foot with respect to the obstacle is very important as it alters the timing of the occurrence of the obstacle during the stride cycle. Previous studies which have looked at the kinematics of obstacle crossing [27, 33] have emphasized the importance of correct positioning of the trailing foot, as it dictates the subsequent lower extremity kinematics, and thus the level of success in crossing the obstacle. Small horizontal clearances between the trailing toe and the obstacle have been shown to cause contact with the obstacle with the toe of the lead foot [27], while large clearances increases the probability of stepping on the obstacle with the heel of the lead foot. In addition, Chou and Draganich [34] demonstrated that reducing the trailing toe-obstacle clearance inevitably causes a reduction in flexion of the lower extremities, which decreases the vertical clearance between the lead foot and the obstacle.

Our studies indicated that, although not statistically significant, TC practitioners displayed smaller toe-obstacle clearances, and hence smaller vertical clearances for the lead and trailing foot. It must be noted, however, that none of the subjects came in contact with the obstacle, tripped, nor fell, while crossing the obstacle. Chou [35] suggested that when crossing obstacles, conservation of energy becomes a less dominant criterion for governing the motion of the swing limb than when walking on level ground. Strategies, hence, might be influenced by additional parameters such as optimizing neural control of the muscles, or minimizing the dangers of tripping. While Chou [35] investigated obstacles ranging only up to 20.4 cm, our most challenging obstacle is 40 cm tall. In addition, previous studies [27] and our study observed that vertical clearances increase with an increase in the height of the obstacle. A greater amount of energy is expended to generate greater clearances, which suggests that the best strategy to cross the most challenging obstacle condition might require a trade-off between generating safe vertical clearances and minimizing energy expenditure. Hence, optimizing the vertical clearance becomes more important for the tallest obstacle. Further investigation addressing the above factors is required before we can comment on the strategies used by the two groups to produce the observed obstacle-foot clearances.

We also hypothesized that Tai Chi practitioners would walk with wider steps based on their significantly wider stance adopted during quiet stance [19]. Our data did support this hypothesis, though results were not statistically significant.

Variability in stride characteristics has been regarded as an indicator of stability during gait, and hence a potential predictor of falling. Previous studies which have examined variability during

gait have found increased variability in step-to-step double support and stride time [36], stance and swing duration [37], and stride length [38] to be associated with falling. Hausdorff [37] also suggested that measures of stride-to-stride fluctuations in gait may be used to help augment the identification of older adults most likely to benefit from interventions like Tai Chi. Hence, we assessed variability in step length, width and speed during normal walking by examining the coefficient of variation, which is defined as the standard deviation normalized by the mean expressed as a percentage. To increase the number of steps evaluated, data from three trials were pooled together; thus the mean and standard deviation for each parameter were calculated over 15 steps i.e. five from each trial [39]. We found that, although not statistically significant $(p > 0.034)$, TC practitioners appeared to be slightly less variable in the above gait parameters.

As a follow-up to this work, we hope to identify other parameters that can significantly quantify differences in movement strategies and balance with Tai Chi experience. In addition, we are also interested in gaining an insight into how these strategies develop or change as a person learns Tai Chi.

3.5. Conclusions

This is the first among many studies which aims at understanding the underlying mechanisms that may modify gait and balance strategies as a function of exercise, specifically Tai Chi. As hypothesized, we found that experienced TC practitioners utilized more cautious strategies in modifying their stride characteristics, when asked to step over obstacles of two different heights. In comparison to their age, gender and activity matched controls, TC practitioners walked with

slower individual step speeds, and hence with a slower overall average speed, took shorter steps, and spent longer time in single leg support when crossing the obstacles. Interestingly, TC practitioners also appeared to place their trailing foot closer to the obstacle prior to crossing it, and the lead foot closer to the obstacle after crossing it when compared to the controls. As observed from previous research, the above strategy forced them to produce smaller vertical clearances between the obstacle, and both the lead and trailing feet. Previous studies on obstacle crossing suggests that smaller vertical clearances essentially puts a person at a greater risk for falling; however, further investigation addressing issue of optimality is required before a conclusion can be made.

3.6. List of References

1. Yang, Y., *Taijiquan: the art of nurturing, the science of power.* Zhenwu Press, Champaign, IL, in press.
2. Channer, K.S., et al., *Changes in haemodynamic parameters following Tai Chi Chuan and aerobic exercise in patients recovering from acute myocardial infarction.* Postgraduate Medical Journal, 1996. **72**(848): pp. 349-351.
3. Young, D.R., et al., *The effects of aerobic exercise and T'ai Chi on blood pressure in older people: results of randomised trial.* Journal of the American Geriatrics Society, 1999. **47**(3): pp. 277-284.
4. Jin, P.T., *Efficacy of Tai Chi, brisk walking, meditation, and reading in reducing mental and emotional stress.* Journal of Psychosomatic Research, 1992. **36**(4): pp. 361-370.
5. Sandlund, E.S. and T. Norlander, *The effects of Tai Chi Chuan relaxation and exercise on stress responses and well-being: an overview of research.* International Journal of Stress Management, 2000. **7**(2): pp. 139-149.
6. Kirsteins, A.E., F. Dietz, and S.M. Hwang, *Evaluating the safety and potential use of a weight-bearing exercise, Tai-Chi Chuan, for rheumatoid arthritis patients.* American Journal of Physical Medicine and Rehabilitation, 1991. **70**(3): pp. 136-141.
7. Husted, C., L. Pham, and A. Hekking, *Improving quality of life for people with chronic conditions: the example of T'ai Chi and multiple sclerosis.* Alternative Therapies in Health and Medicine, 1999. **5**(5): pp. 70-74.
8. Howell, C.J., *The therapeutic effect of Tai Chi in the healing process of HIV.* International Journal of Alternative and Complementary Medicine, 1999. **Nov**: pp. 15-19.
9. Kutner, N.G., et al., *Self-report benefits of Tai Chi practice by older adults.* Journal of Gerontology Series B: Psychological Sciences and Social Sciences, 1997. **52**(5): pp. 242-246.

10. Li, F., et al., *An evaluation of the effects of Tai Chi exercise on physical function among older persons: a randomized contolled trial.* Annals of Behavioral Medicine, 2001. **23**(2): pp. 139-146.
11. Li, J.X., Y. Hong, and K.M. Chan, *Tai chi: physiological characteristics and beneficial effects on health.* British Journal of Sports Medicine, 2001. **35**(3): pp. 148-156.
12. Lan, C., et al., *Cardiorespiratory function, flexibility, and body composition among geriatric Tai Chi Chuan practitioners.* Archives of Physical Medicine and Rehabilitation, 1996. **77**(6): pp. 612-616.
13. Province, M.A., et al., *The effects of exercise on falls in elderly patients. A preplanned meta-analysis of the FICSIT Trials.* Journal of American Medical Association, 1995. **273**(17): pp. 1341-1347.
14. Wolf, S.L., et al., *Reducing frailty and falls in older persons: an investigation of Tai Chi and computerized balance training.* Journal of the American Geriatrics Society, 1996. **44**: pp. 489-497.
15. Wolf, S.L., et al., *Intense tai chi exercise training and fall occurrences in older, transitionally frail adults: a randomized, controlled trial.* Journal of the American Geriatrics Society, 2003. **51**(12): pp. 1693-1701.
16. Nowalk, M.P., et al., *A randomized trial of exercise programs among older individuals living in two long-term care facilities: the Falls FREE program.* Journal of the American Geriatrics Society, 2001. **49**(7): pp. 859-865.
17. Mak, M.K. and P.L. Ng, *Mediolateral sway in single-leg stance is the best discriminator of balance performance for Tai-Chi practitioners.* Archives of Physical Medicine and Rehabilitation, 2003. **84**(5): pp. 683-686.
18. Wolfson, L., et al., *Balance and Strength Training in Older Adults - Intervention Gains and Tai Chi Maintenance.* Journal of the American Geriatrics Society, 1996. **44**(5): pp. 498-506.
19. Rosengren, K.S., et al., *A comparison of balance in individuals with significant dance or Taiji experience.* Gait and Posture, in review
20. Tse, S.K. and D.M. Bailey, *T'ai chi and postural control in the well elderly.* American Journal of Occupational Therapy, 1992. **46**(4): pp. 295-300.
21. Schaller, K.J., *Tai Chi Chih: an exercise option for older adults.* Journal of Gerontological Nursing, 1996. **22**(10): pp. 12-17.
22. Ross, M.C., et al., *The effects of a short-term exercise program on movement, pain, and mood in the elderly. Results of a pilot study.* Journal of Holistic Nursing, 1999. **17**(2): pp. 139-147.
23. Hartman, C.A., et al., *Effects of T'ai Chi training on function and quality of life indicators in older adults with osteoarthritis.* Journal of the American Geriatrics Society, 2000. **48**(12): pp. 1553-1559.
24. Hong, Y., J.X. Li, and P.D. Robinson, *Balance control, flexibility, and cardiorespiratory fitness among older Tai Chi practitioners.* British Journal of Sports Medicine, 2000. **34**(1): pp. 29-34.
25. Song, R., et al., *Effects of tai chi exercise on pain, balance, muscle strength, and perceived difficulties in physical functioning in older women with osteoarthritis: a randomized clinical trial.* Journal of Rheumatology, 2003. **30**(9): pp. 2039-2044.
26. Tinetti, M.E., et al., *Risk factors for serious injury during falls by older persons in the community.* Journal of the American Geriatrics Society, 1995. **43**(11): pp. 1214-1221.

27. Chen, H.-C., et al., *Stepping over obstacles: gait patterns of healthy young and old adults.* Journal of Gerontology: Medical Sciences, 1991. **46**(6): pp. M196-M203.
28. Lamoureux, E., et al., *The effects of improved strength on obstacle negotiation in community-living older adults.* Gait and Posture, 2003. **17**(3): pp. 273-283.
29. Begg, R.K. and W.A. Sparrow, *Gait characteristics of young and older individuals negotiating a raised surface: implications for the prevention of falls.* Journal of Gerontology Series A: Biological Sciences and Medical Sciences, 2000. **55**(3): pp. M147-154.
30. Rosengren, K.S., E. McAuley, and S.L. Mihalko, *Gait adjustments in older adults: activity and efficacy influences.* Psychology and Aging, 1998. **13**(3): pp. 375-386.
31. Murray MP, Kory RC, Clarkson BH, *Walking patterns in healthy old men.* Journal of Gerontology, 1969. 24(2): pp. 169-178.
32. Berg, K.O., et al., *Measuring balance in the elderly: validation of an instrument.* Canadian Journal of Public Health, 1992. 83 Suppl 2: pp. S7-S11.
33. Chou, L.S., et al., *Medio-lateral motion of the center of mass during obstacle crossing distinguishes elderly individuals with imbalance.* Gait and Posture, 2003. **18**(3): pp. 125-133.
34. Chou, L.S. and L.F. Draganich, *Placing the trailing foot closer to an obstacle reduces flexion of the hip, knee, and ankle to increase the risk of tripping.* Journal of Biomechanics, 1998. **31**(8): pp. 685-691.
35. Chou, L.S. and L.F. Draganich, *Stepping over obstacles increases the motions and moments of the joints of the trailing limb in young adults.* Journal of Biomechanics, 1997. **30**(4): pp. 331-337.
36. Gabell, A. and U.S. Nayak, *The effect of age on variability in gait.* Journal of Gerontology, 1984. **39**(6): pp. 662-666.
37. Hausdorff, J.M., et al., *Increased gait unsteadiness in community-dwelling elderly fallers.* Archives of Physical Medicine and Rehabilitation, 1997. **78**(3): pp. 278-283.
38. Maki, B.E., *Gait changes in older adults: predictors of falls or indicators of fear.* Journal of the American Geriatrics Society, 1997. **45**(3): pp. 313-320.
39. Brach, J.S., et al., *Gait variability in community-dwelling older adults.* Journal of the American Geriatrics Society, 2001. **49**(12): pp. 1646-1650.

3.7. Tables and Figures

Table 3.1. Subject demographics and exercise behaviors (mean ± sd).

	Tai Chi (n = 15)	Controls (n = 15)	p – value[#]
Females	7	7	--
Mean age (y)	45.7 ± 10.6	45.7 ± 9.9	0.986
Age range (y)	25 - 66	24 - 63	--
Weight (kg)	70.4 ± 11.5	72.4 ± 12.7	0.666
Height (cm)	169 ± 5	172 ± 9	0.171
Activity level* (days/wk)	5.8 ± 0.9	4.9 ± 1.1	0.020
Exercise Intensity (1 - 4 scale)	2.2 ± 0.56	3 ± 0.65	0.001
Type of activity[§] (n, %)			
Walking	26	24	--
Running	0	41	--
Biking	17	18	--
Other	57	18	--
Tai Chi practice frequency (hrs/wk)	7.68 ± 3.46	--	--

* Physical activity level was reported as the average number of days per week with exercise bouts of 30 minutes or more.

[§] Physical activities other than Tai Chi.

[#] Based on unpaired *t*-tests.

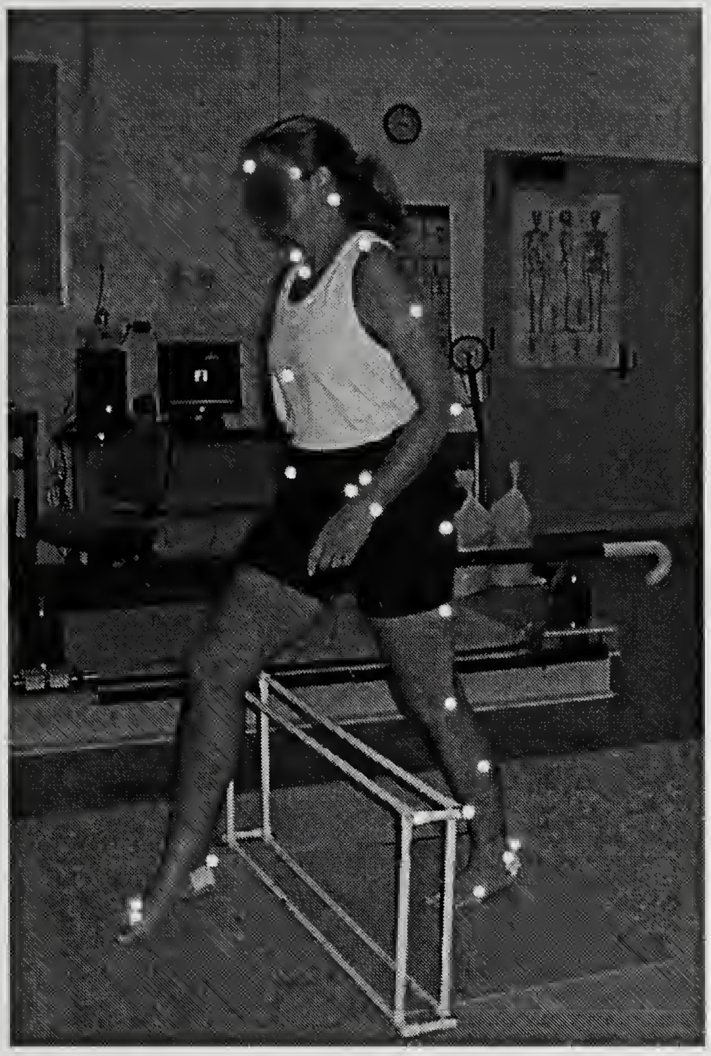

Figure 3.1. Experimental protocol. Test subjects walked barefoot over a 9.8 m elevated walkway that had no obstacle, a 10 cm obstacle, or a 40 cm obstacle (shown) placed over the distant portion of the force plate. Only trials where a single foot strike landed within the force plate were recorded. Kinematic data from reflective markers placed on the top corners of the obstacle and the subject's toes (1^{st} metatarsal) and heels (calcaneous) were used to compute gait parameters.

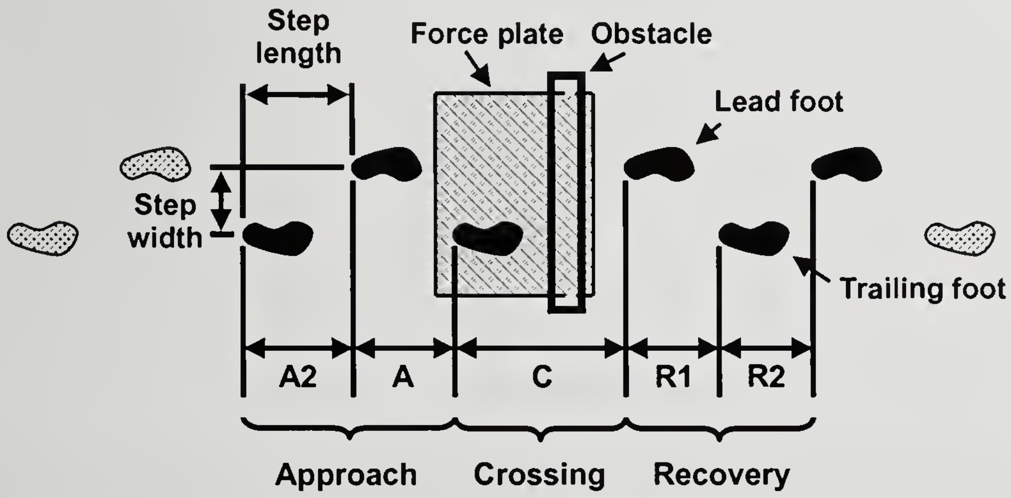

Figure 3.2. Five step positions used in gait parameter calculations. The steps were classified as occurring before the obstacle (*approach*), after the obstacle (*recovery*), and during obstacle crossing (*crossing*). Step length, step width, and step speed were determined for each consecutive step position based on heel strike events.

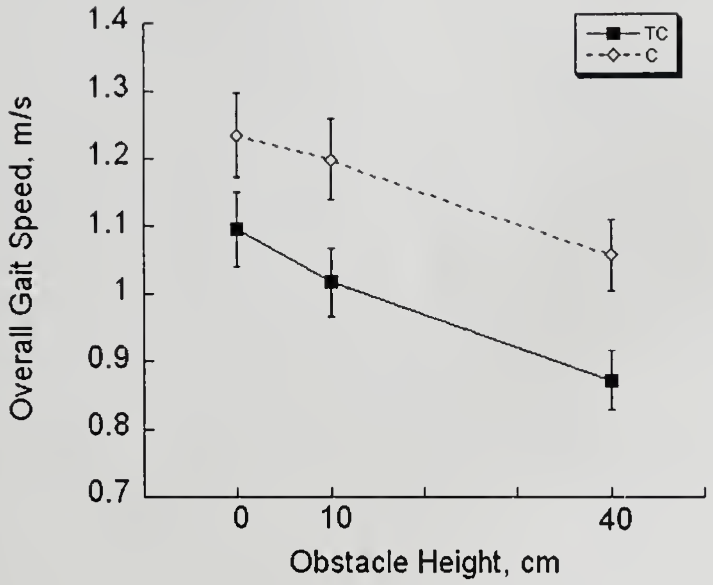

Figure 3.3a. Mean overall gait speed as a function of group and obstacle height. Error bars denote standard error. Gait speed was based on the time to cover a distance of 3.5m. Solid line represents TC practitioners, dashed line represents control subjects.

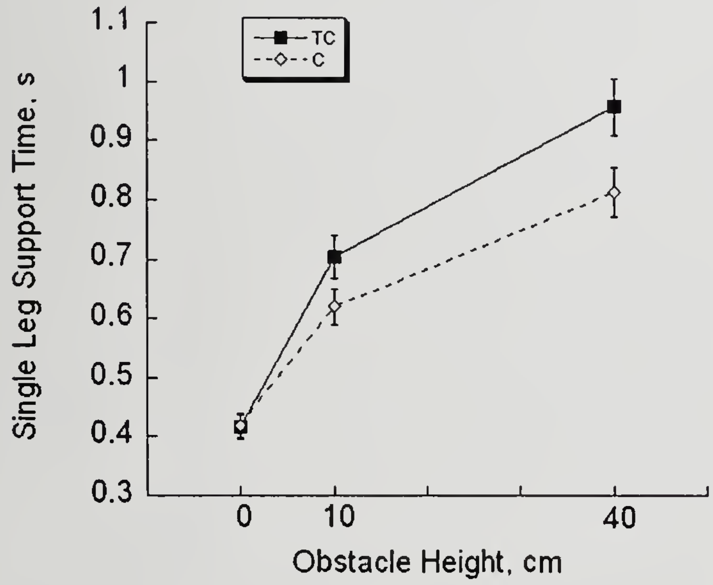

Figure 3.3b. Mean time spent in single leg support for the crossing step. The time was calculated from toe-off just prior to crossing the obstacle to heel strike after crossing the obstacle for the lead foot.

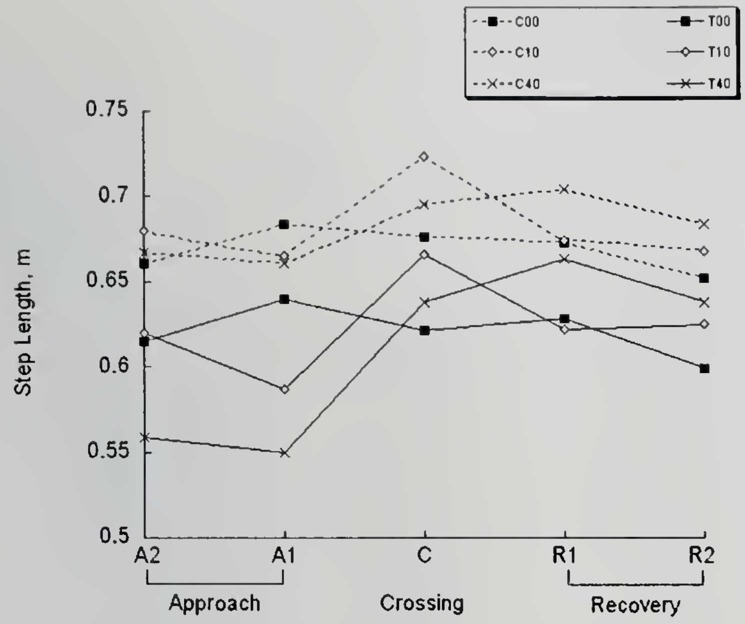

Figure 3.4a. Step length as a function of group and obstacle height. Step length was defined between successive heel strikes, for the five step positions analyzed.

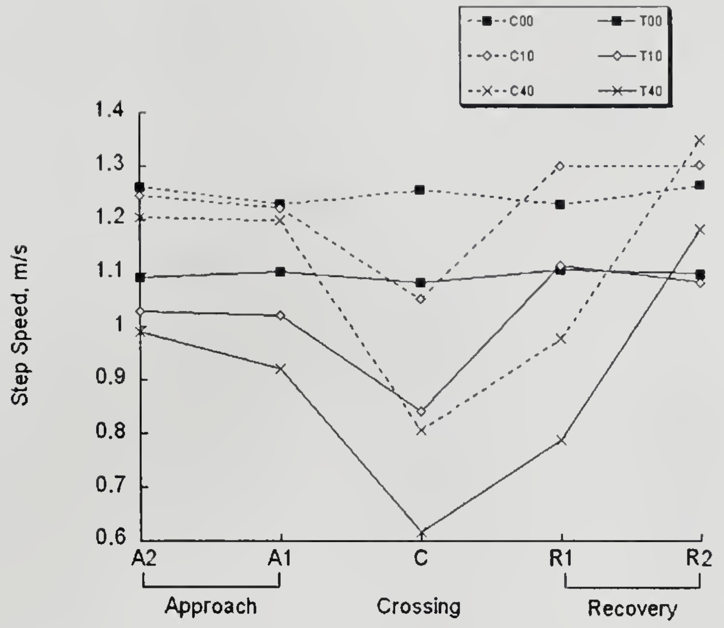

Figure 3.4b. Individual step speed as a function of group and obstacle height. Step speed was defined as the ratio of the step lengths for the five step positions analyzed, to the time interval between heel strikes defining the five steps.

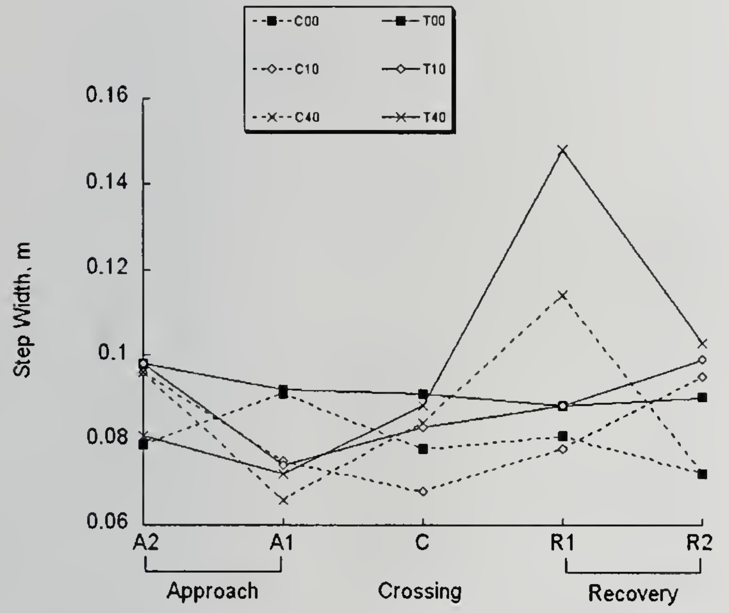

Figure 3.4c. Step width as a function of group and obstacle height. Step width was defined as the medial-lateral displacement of the heel marker between successive heel strikes.

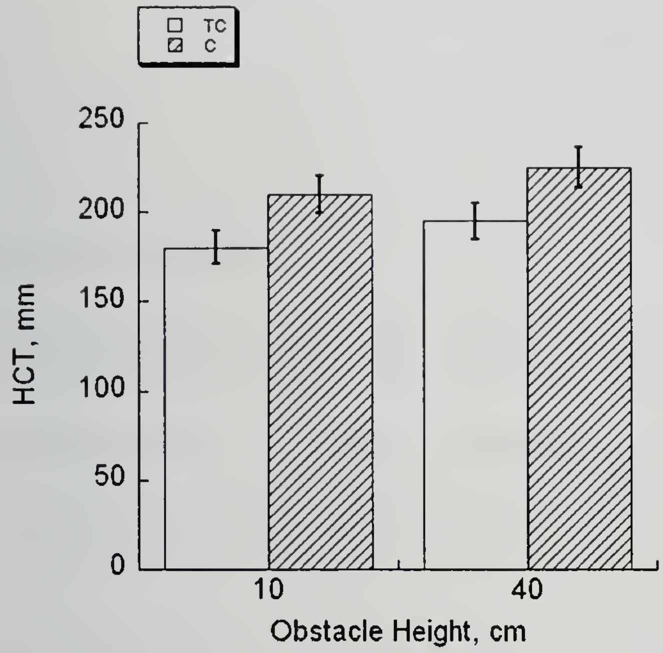

Figure 3.5a. Horizontal clearance between toe of the trailing foot at heel strike immediately prior to crossing the obstacle, and the front of the obstacle. The zero line represents the front of the obstacle.

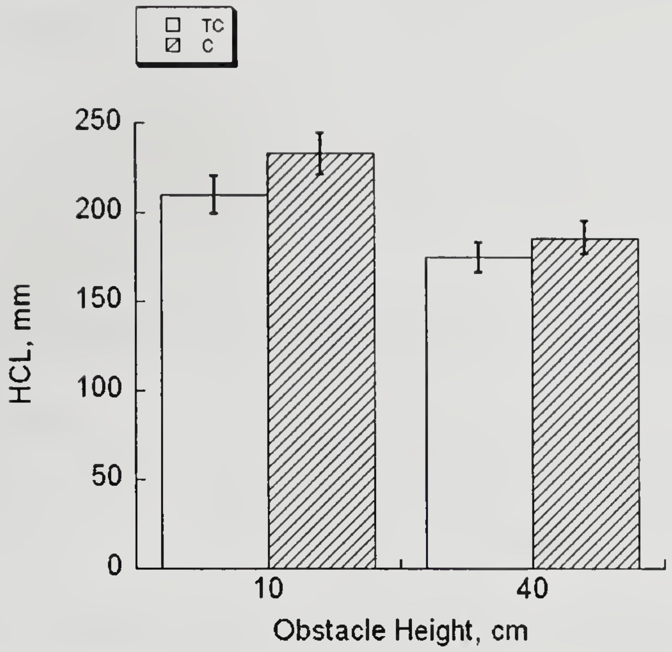

Figure 3.5b. Horizontal clearance between the heel of the leading foot at heel strike immediately after crossing the obstacle, and the back of the obstacle. The zero line represents the back of the obstacle.

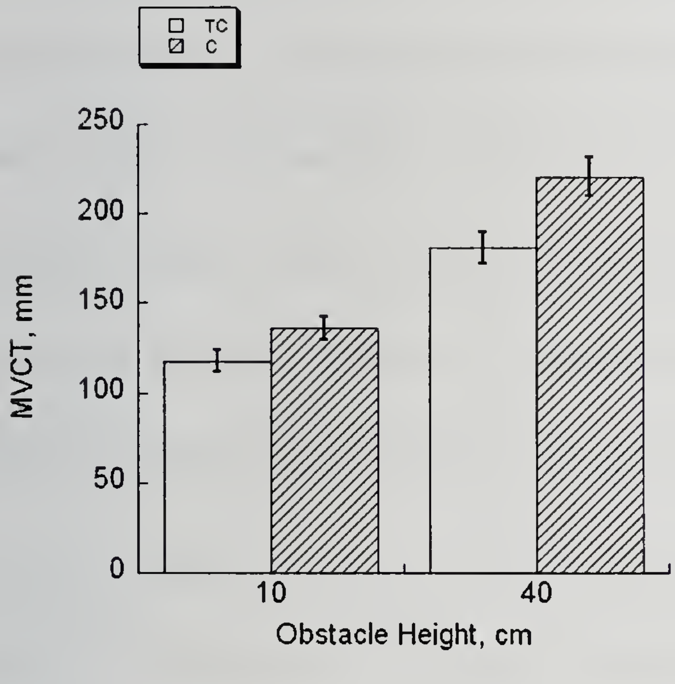

Figure 3.5c. Minimum vertical clearance between the trailing foot (toe or heel) and the obstacle (front or back), during the crossing step. The zero line represents the top surface of the obstacle.

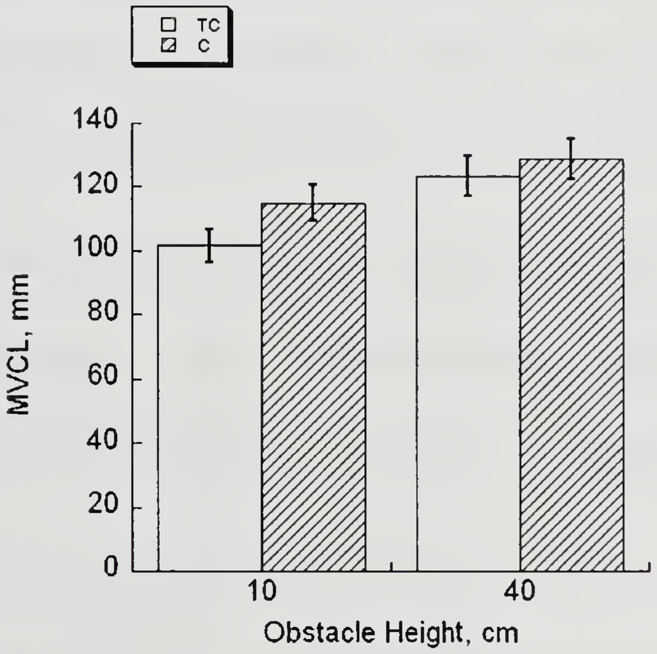

Figure 3.5d. Minimum vertical clearance between the leading foot (toe or heel) and the obstacle (front or back), during the crossing step. The zero line represents the top surface of the obstacle.

CHAPTER 4: EFFECT OF TAI CHI TRAINING IN OLDER ADULTS ON OBSTACLE CROSSING STRATEGY

4.1. Introduction

Falls has been reported to account for significant number of injuries in the elderly [1-3]. A major cause for falls is imbalance and tripping over obstacles during gait [2, 4-7]. Obstacle crossing in the elderly population has hence received increased attention in the scientific community. Chen and colleagues [8] conducted one of the first studies to investigate gait patterns of young and old adults in stepping over obstacles. They reported that old adults were more conservative in using slower approach and crossing speeds when crossing obstacles and their foot placement was such that they crossed the obstacle farther forward in the swing phase of the crossing cycle. However, much of their analyses were restricted to kinematics of the crossing step due to limitations of their experimental setup. A study by Rosengren and colleagues [9] investigated the effect of physical activity level and gait related self-efficacy cognitions on kinematic variables, such as step length, step velocity, and time in single leg support. They tested fifty-five community dwelling older adults as they crossed over obstacles of increasing height. They found that, compared to active older adults, sedentary older adults adopted a more cautious walking style, exhibiting shorter step lengths and slower step velocities. Their study was the first to quantify changes in gait strategies over multiple steps during obstructed gait, wherein three steps prior to and after crossing the obstacle were analyzed. This enabled them to observe how early an obstacle disrupted the gait cycle and how long it took an individual to recover their normal gait. Intervention programs aimed at improving balance in elderly adults have been gaining increasing popularity. One recent study by Lamoureux et al [10] performed a biomechanical analysis to

assess the effects of a strength training intervention program on gait mechanics associated with obstacle negotiation. They argued that the kinematic and kinetic variables obtained would provide insight into the effectiveness of the intervention and reveal the mechanisms underpinning exercise-induced changes in gait mechanics in community-dwelling older adults. From their results, they suggested that a gain in lower body strength due to the intervention led to a more effective obstacle crossing strategy, wherein subjects significantly increased their vertical heel clearance by generating greater vertical propulsive force and increased knee and ankle flexion. The authors concluded that the gain in strength allowed the subjects to adopt this safer strategy even though it was at a higher energy cost. They also observed that subjects landed farther from the obstacle after crossing with a decreased vertical descending velocity of the foot, thus providing greater control in avoiding a trip.

Because of its appeal as a slow and non-strenuous exercise that is conducive to group interaction, Tai Chi has been promoted to older adults as an intervention to improve physical and mental fitness [11-13], improve cardio-respiratory function [14], and prevent falls [15]. In a seminal study, Wolf and colleagues found that healthy older adults who practiced Tai Chi for 15 weeks delayed the onset of falls by 47.5% when compared to individuals that received either computerized balance training or a wellness education program [16]. More recently, Wolf et al. [17] and Nowalk et al. [18] conducted randomized control tests on less robust older adults that were living in congregate living or long-term care facilities. Neither study found statistically significant differences between groups; however, both studies did note trends in fall reduction due to Tai Chi experience. Tai Chi training emphasizes enhanced attention when moving through a given environment and enhanced awareness of one’s balance limitations [19]. It is possible that

this training may cause Tai Chi practitioners to modify their movement strategies and move more cautiously through their surroundings, which may provide some explanation for these observed reductions in falls.

A previous study conducted by the authors (Chapter 3) on obstacle crossing strategies revealed that experienced Tai Chi practitioners utilized more cautious strategies in modifying their stride characteristics, when asked to step over obstacles of two different heights. In comparison to their age, gender and activity matched controls, Tai Chi practitioners walked with slower individual step speeds, and hence with a slower overall average speed, took shorter steps, and spent longer time in single leg support when crossing the obstacles. Interestingly, Tai Chi practitioners also appeared to place their trailing foot closer to the obstacle prior to crossing it, and the lead foot closer to the obstacle after crossing it when compared to the controls. Based on the results, we hypothesize that training in Tai Chi would induce similar trends in the behavior of the elderly adults.

4.2. Methods

4.2.1. Participants

Eighteen subjects were recruited from three senior residences and tested at three intervals: prior to the start of the intervention *(T0)*, after two months of training (*T2*), and after five months of training (*T5*). Two participants dropped out of the program between T0 and T2, and two more participants dropped out between T2 and T5. Therefore, in this study, all data are based on the remaining fourteen subjects (9 females, 5 males; age: 74.3 ± 7.5 years; age range: 61 – 87 years; weight: 76.97 ± 14.01 kgs; height: 163.04 ± 8.8 cm). The study was approved by the Institutional

Review Board of the University of Illinois. Informed consent was obtained from each subject prior to participation.

4.2.2. Experimental Procedure

Subjects were instructed to walk barefoot at a self-selected pace along a 9.8 m elevated (0.11 m high × 1.8 m wide) walkway. Three conditions were tested: no obstacle (*00*), 10 cm obstacle (*10*), and 30 cm obstacle (*30*). Conditions were presented in order of increasing obstacle height. Both obstacles measured 10 cm in width and 113 cm in length, and were placed in the middle of the walkway. Subjects were allowed to walk around the obstacle if they were not comfortable with stepping over it.

Kinematic data were collected using a 6-camera optical motion capture system (Vicon Motion Systems, Oxford, UK; Datastation 460) that was sampled at 100 Hz and then filtered using a recursive 4th order Butterworth low-pass filter with a cut-off frequency of 6 Hz. Thirty-six markers were attached to the subject; however only data from markers placed at the left and right calcaneous (heel), 1st metatarsal heads (toe), and sacrum were used in this study. Markers were also placed on the top four corners of the obstacle. Kinematic data were collected for the central 3.5 m of the walkway, which spanned the capture volume of the camera set-up. For each test condition, data were collected for two trials. Only one trial for which clean kinematic data were available was used for further analysis.

4.2.3. Data Analysis

For each trial, we examined five consecutive steps: two "approach" steps, one "crossing" step, and two "recovery" steps, which were defined at heel strike. We used these five steps since we were able to consistently measure at least these five steps within our capture volume for all subjects. The crossing step for the no-obstacle trials was determined from approximate placement of the feet relative to the standard location of the obstacle in obstacle crossing conditions.

4.2.3.1. Gait Parameters

For each of the five step positions, the following gait parameters were computed for each trial (*Figure 4.1*): anterior-posterior step length (SL), medial-lateral step width (SW), and average step speed between consecutive steps (SS). The time in single leg support (SLST) while crossing the obstacle was defined as the time duration that the trailing limb was in single leg support, i.e., from the instant of toe-off to heel strike of the lead foot (first foot over the obstacle) while it crossed over the obstacle. Average gait speed (*gait speed*) was computed over a distance of 3.5m and based on temporal data for the sacral marker.

4.2.3.2. Obstacle-Foot Clearance Parameters

Vertical and horizontal clearance values were calculated between the foot and obstacle for both the lead and trailing feet during obstacle crossing trials. We refer to the approach side of the obstacle as the obstacle "front" and the recovery side as the obstacle "back". For all calculations, the location of the front or back of the obstacle was determined from the average vertical and horizontal positions of the two reflective markers on the respective side. The minimum vertical

clearance for the lead (*MVCL*) or trailing (*MVCT*) foot was defined as the minimum of four measurements based on when the heel or toe marker was vertically above the front or back top edge of the obstacle (*Figure 4.2a*). The horizontal clearance between the obstacle front side and the toe marker on the trailing foot (*HCT*) was calculated at the instant of heel strike of the trailing foot during the crossing step. Similarly, the horizontal clearance between the obstacle back side and the heel marker on the lead foot (*HCL*) was calculated at the instant of heel strike of the lead foot immediately after crossing the obstacle (*Figure 4.2b*).

4.2.4. Statistical Analysis

Two-way repeated measures analysis of variance (ANOVA) were performed to examine the effects of obstacle height and training on the step length, step speed, step width, overall gait speed, time in single leg support, MVCL, MVCT, HCT, and HCL. Obstacle height had three levels (00, 10 and 30), and training month had three levels (T0, T2 and T5).

Significant differences and interactions were verified using Tukey HSD post-hoc comparisons. A ‘p’ value of 0.05 was chosen to represent significance. All statistical analyses were run on SPSS v12 (SPSS, Inc., Chicago, IL).

4.3. Results

4.3.1. Gait Parameters

Two subjects out of fourteen tested in this study had difficulty stepping over the obstacles consistently during T0, T2 and T5. The first subject walked around both obstacles during T0, stepped over the 10 cm obstacle but walked around the 30 cm obstacle during T2, and walked

around both obstacles during T5. The second subject crossed the 10 cm obstacle without tripping or falling, but contacted the rear end of the obstacle with the heel of the leading foot, and walked around the 30 cm obstacle during T0, walked around both obstacles during T2, and successfully crossed the 10 cm obstacle, but walked around the 30 cm obstacle during T5. The remaining twelve subjects crossed both obstacles without tripping, or falling, and never came in contact with the obstacle. The following results are reported for the twelve subjects only.

4.3.1.1. Overall Gait Speed

Figure 4.3a shows the average overall gait speed of the participants as a function of obstacle height and training month. Training month did not have a significant effect on the gait speed ($p = 0.274$). Gait speed was significantly affected by obstacle height ($p<0.001$). Post-hoc tests revealed that subjects significantly reduced their average speed from 1.125 m/s (*SE: 0.05*) during normal unobstructed walking to 0.99 m/s (*0.05*) for the 10 cm obstacle, and 0.89 m/s (*0.04*) for the 30 cm obstacle.

4.3.1.2. Step Lengths

No significant differences were found in step lengths across the three testing periods ($p > 0.235$, *Figure 4.4a*). Obstacle height had a significant main effect on the approach (*AL2:* $p = 0.006$, *AL1:* $p = 0.003$) and crossing lengths step (*CL:* $p = 0.027$). Subjects were found to significantly decrease their approach step lengths and increase their crossing step length, with increase in obstacle height.

4.3.1.3. Step Speeds

Step speeds did not differ significantly with training month ($p > 0.112$); however, obstacle height had a significant main effect on the two approach steps, the crossing step, and the first recovery step ($p < 0.001$, *Figure 4.4b*). Post-hoc comparisons revealed that mean step speeds differed significantly between unobstructed walking (*00*) and obstructed walking (*10, 30*) for the approach steps, while it differed between all three obstacle conditions for the crossing and the first recovery step.

4.3.1.4. Step Widths

Training month did not have a significant effect on any of the five step widths analyzed with respect to position ($p > 0.392$, *Figure 4.4c*). Step width of the crossing step significantly increased with obstacle height ($p = 0.004$). Post-hoc tests verified that the crossing step width for the tallest obstacle i.e., 30 cm, (*00:* $M = 109.94mm$, $SE = 14.36$; *10:* $M = 111.45mm$, $SE = 15.26$; *30:* $M = 161.5mm$, $SE = 19.54$) was significantly greater than other two conditions. Step widths for other step positions were not significantly with respect to obstacle height.

4.3.1.5. Time in Single Leg Support

The time spent in single leg support was not affected by training month ($p = 0.381$). Only obstacle height was found to significantly increase single leg support time ($p < 0.001$). Post-hoc tests revealed that single leg support time was significantly different between the three obstacle conditions (*00:* $M = 0.53s$, $SE = 0.015$; *10:* $M = 0.65s$, $SE = 0.025$; *30:* $M = 0.80s$, $SE = 0.027$; *Figure 4.3b)*.

4.3.2. Obstacle-Foot Clearance Parameters

4.3.2.1. Vertical Clearances

The minimum vertical clearance for the lead foot was found to be significantly affected by training month (*p = 0.034*), and obstacle height (*p = 0.02*). Subjects increased their lead foot clearance significantly over the three testing periods (*T0: M = 155.07mm, SE = 17.87; T2: M = 169.29mm, SE = 17.12; T5: M = 180.93mm, SE = 11.73, Figure 4.5c)*. Trends also indicated that the trailing foot clearance increased over the three testing periods, though the result was not significant (*p = 0.947, Figure 4.5d*). Vertical clearance for the lead foot also increased significantly with height (*p = 0.02; 10: M = 160 mm, SE = 14; 30: M = 176 mm, SE = 16*).

4.3.2.2 Horizontal Clearances

Neither training month nor obstacle height significantly affected either horizontal clearance (*p > 0.24*). Non-significant trends suggested that subjects positioned their trailing foot farther away from the 30cm obstacle (*M = 224 mm, SE = 11*) and the lead foot closer to the 30cm obstacle after crossing it (*M = 120 mm, SE = 12*) compared to the 10cm obstacle (*M = 212 mm, SE = 14, Trailing foot; M = 127 mm, SE = 12, Leading foot*). No consistent trends were found with the training month. Figures 4.5a and 4.5b display the horizontal clearances for the lead and trailing foot, respectively, as a function of obstacle height and training month.

4.4. Discussion

This study was conducted on elderly adults to search for gait parameters, during obstructed and unobstructed walking, which would potentially vary across the duration of Tai Chi training over a five month period. Based on a previous study (Chapter 3) where we found that experienced Tai

Chi practitioners modified their gait strategy by taking shorter and slower steps in approaching and crossing obstacles of different heights in their path, we had hypothesized that training in Tai Chi would induce similar trends in the behavior of the elderly adults. In order to first identify common trends statistically, all subjects were pooled together as a group. The data revealed that only the minimum vertical clearance between the obstacle and the lead foot (*MVCL*) significantly increased over time (Figure 3c). MVCL also increased with increasing obstacle height. None of the other gait parameters were significantly affected by training month; however, some nonsignificant trends were noted with other obstacle-foot clearance parameters. This result suggests a positive trend reflecting the gain in the ability of the subjects to increase clearance with Tai Chi training. Figure 3d reveals that the vertical clearance of the trailing foot (*MVCT*) tended to increase over time for the 10cm obstacle; however, no trends were observed for the 30cm obstacle. Previous research has shown that flexion at the knee favors flexion at the hips to elevate the foot in order to step over obstacles with a safe vertical clearance [20]. Further analysis is hence required to investigate the lower extremity kinematics in order to understand the relative contributions of the various joints in producing the observed clearance, and how they differed across the training. Although not statistically significant, horizontal placement of the trailing foot with respect to the obstacle was farther away for the 30cm obstacle compared to the 10cm obstacle. The lead foot also tended to be positioned closer to the 30cm obstacle after stepping over it. This strategy might suggest that subjects attempted to cross the more challenging obstacle later in the gait cycle.

Gait parameters appeared to be influenced by obstacle height. Consistent with our previous findings reported in Chapter 3, the overall gait speed decreased significantly for the obstructed

walking compared to normal walking. This was primarily achieved by significantly reducing the approach steps and the crossing step speeds during the obstructed walking trials. Decrease in the crossing speed was also reflected in increased times in single leg support as the obstacle height increased. Subjects also reduced their approach step lengths, and increased their crossing step lengths significantly for the obstructed trials when compared to normal walking. The crossing step width was also found to increase with increasing obstacle height, suggesting that the 30cm obstacle produced a greater perturbation in the medial-lateral foot placement during crossing.

The results discussed above reflect the common changes in strategy adopted by the elderly adults over time. It is possible that differences in individual skill levels in Tai Chi, which can be attributed to factors like frequency and intensity of practice during the training program, might have influenced the results. In order to identify specific individuals who might have received significantly more benefits from the training, we need to concurrently assess the acquisition of skill in Tai Chi and changes in gait strategy over time. A second set of tests which examine similar modifications to gait over time in age, gender and activity level matched controls would enable us to determine if the observed results were truly a function of training in Tai Chi.

4.5. Conclusions

This study was conducted to observe changes in obstacle crossing strategy in elderly adults as they underwent five months of training in Tai Chi. Kinematic analysis performed on the subjects at the beginning of the training, after two months, and five months of training revealed that, overall, the subjects were able to generate greater vertical clearance on the leading foot, over time. The underlying lower extremity kinematics supporting this behavior needs to be examined.

Subjects were also able to adjust their gait from normal walking when confronted with obstacles of varying height in their path. Their strategy was consistent with our previous research on obstacle crossing. Further analysis is required to identify individuals who were able to significantly change their obstacle crossing strategy due to Tai Chi training.

4.6. List of References

1. Gryfe, C.I., A. Amies, and M.J. Ashley, *A longitudinal study of falls in an elderly population, I: incidence and morbidity.* Age Ageing, 1977. **6**: pp. 201-210.
2. Prudham, D. and J.G. Evans, *Factors associated with falls in the elderly: a community study.* Age Ageing, 1981. **10**(3): pp. 141-146.
3. Tinetti, M.E., M. Speechley, and S.F. Ginter, *Risk factors for falls among elderly persons living in the community.* The New England Journal of Medicine, 1988. **319**: pp. 1701-1707.
4. Blake, A.J., et al., *Falls by elderly people at home: prevalence and associated factors.* Age and Ageing, 1988. **17**: pp. 365-372.
5. Campbell, A.J., et al., *Circumstances and consequences of falls experienced by a community population 70 years and over during a prospective study.* Age Ageing, 1990. **19**(2): pp. 136-141.
6. Overstall, P.W., et al., *Falls in the elderly related to postual imbalance.* British Medical Journal, 1977. **1**: pp. 261-264.
7. Tinetti, M.E. and M. Speechley, *Prevention of falls among the elderly.* The New England Journal of Medicine, 1989. **320**: pp. 1055-1059.
8. Chen, H.-C., et al., *Stepping over obstacles: gait patterns of healthy young and old adults.* Journal of Gerontology: Medical Sciences, 1991. **46**(6): pp. M196-M203.
9. Rosengren, K.S., E. McAuley, and S.L. Mihalko, *Gait adjustments in older adults: activity and efficacy influences.* Psychology and Aging, 1998. **13**(3): pp. 375-386.
10. Lamoureux, E., et al., *The effects of improved strength on obstacle negotiation in community-living older adults.* Gait and Posture, 2003. **17**(3): pp. 273-283.
11. Kutner, N.G., et al., *Self-report benefits of Tai Chi practice by older adults.* Journal of Gerontology Series B: Psychological Sciences and Social Sciences, 1997. **52**(5): pp. 242-246.
12. Li, F., et al., *An evaluation of the effects of Tai Chi exercise on physical function among older persons: a randomized contolled trial.* Annals of Behavioral Medicine, 2001. **23**(2): pp. 139-146.
13. Li, J.X., Y. Hong, and K.M. Chan, *Tai chi: physiological characteristics and beneficial effects on health.* British Journal of Sports Medicine, 2001. **35**(3): pp. 148-156.
14. Lan, C., et al., *Cardiorespiratory function, flexibility, and body composition among geriatric Tai Chi Chuan practitioners.* Archives of Physical Medicine and Rehabilitation, 1996. **77**(6): pp. 612-616.

15. Province, M.A., et al., *The effects of exercise on falls in elderly patients. A preplanned meta-analysis of the FICSIT Trials.* Journal of American Medical Association, 1995. **273**(17): pp. 1341-1347.
16. Wolf, S.L., et al., *Reducing frailty and falls in older persons: an investigation of Tai Chi and computerized balance training.* Journal of the American Geriatrics Society, 1996. **44**: pp. 489-497.
17. Wolf, S.L., et al., *Intense tai chi exercise training and fall occurrences in older, transitionally frail adults: a randomized, controlled trial.* Journal of the American Geriatrics Society, 2003. **51**(12): pp. 1693-1701.
18. Nowalk, M.P., et al., *A randomized trial of exercise programs among older individuals living in two long-term care facilities: the Falls FREE program.* Journal of the American Geriatrics Society, 2001. **49**(7): pp. 859-865.
19. Yang, Y., *Taijiquan: the art of nurturing, the science of power.* in press, Zhenwu Press. Champaign, IL
20. McFadyen, B.J. and D.A. Winter, *Anticipatory locomotor adjustments during obstructed human walking.* Neuroscience Research Communications, 1991. **9**(1).

4.7. Tables and Figures

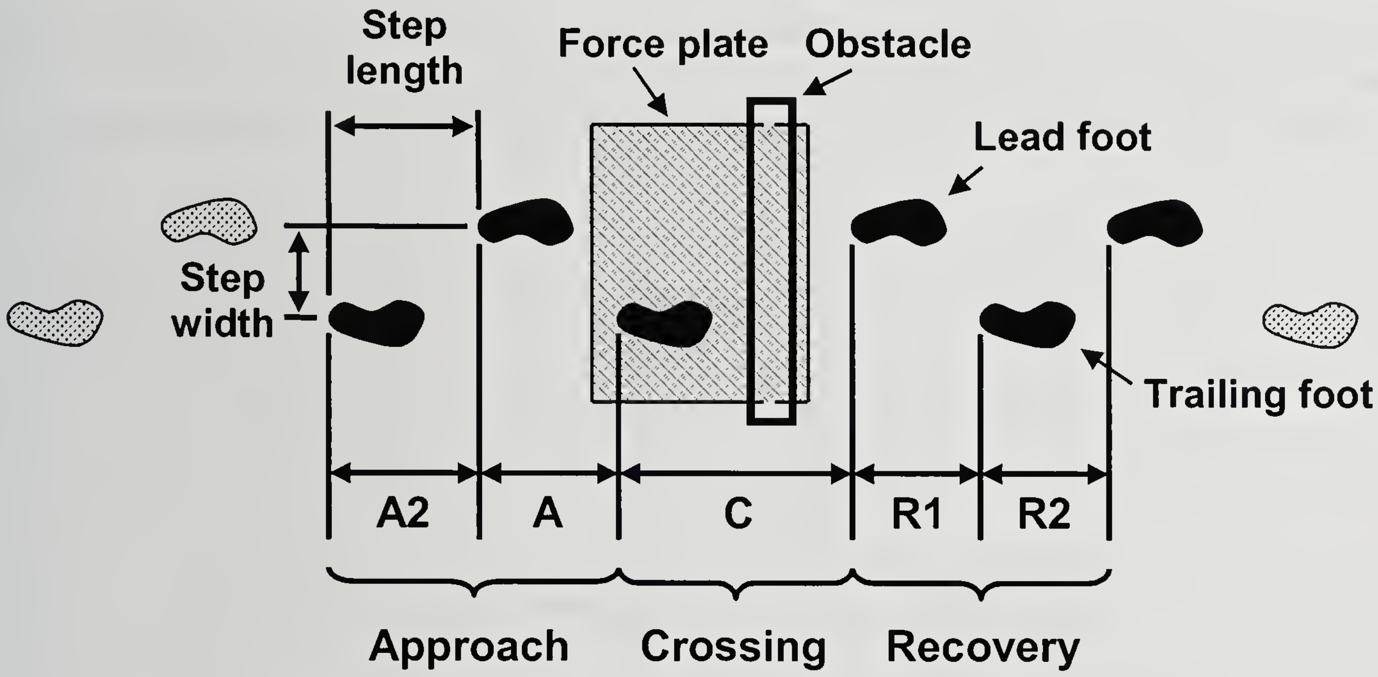

Figure 4.1. Five step positions used in gait parameter calculations. The steps were classified as occurring before the obstacle (*approach*), after the obstacle (*recovery*), and during obstacle crossing (*crossing*). Step length, step width, and step speed were determined for each consecutive step position based on heel strike events.

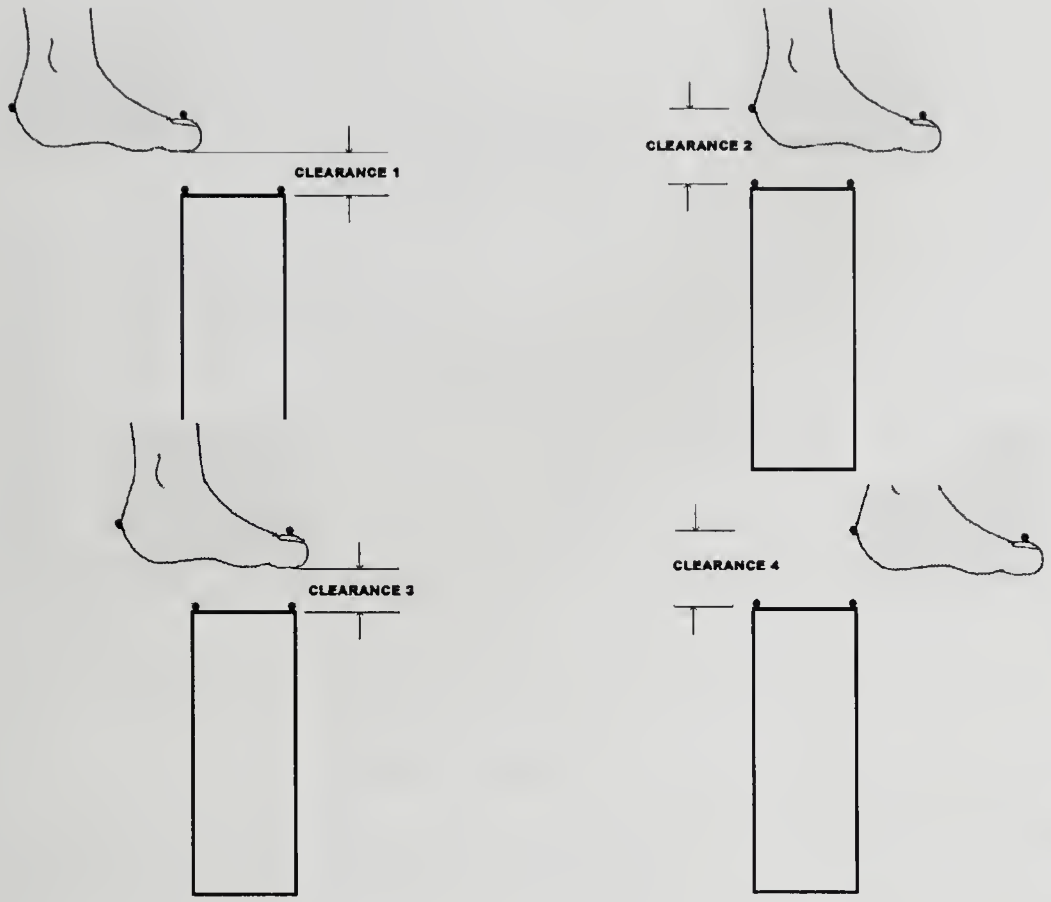

Figure 4.2a. Different foot-obstacle clearances used to determine overall minimum vertical clearance for the lead (*MVCL*) and trailing foot (*MVCT*). Clearances were calculated at four different positions when the heel or toe of the foot was vertically aligned with the front or back of the obstacle.

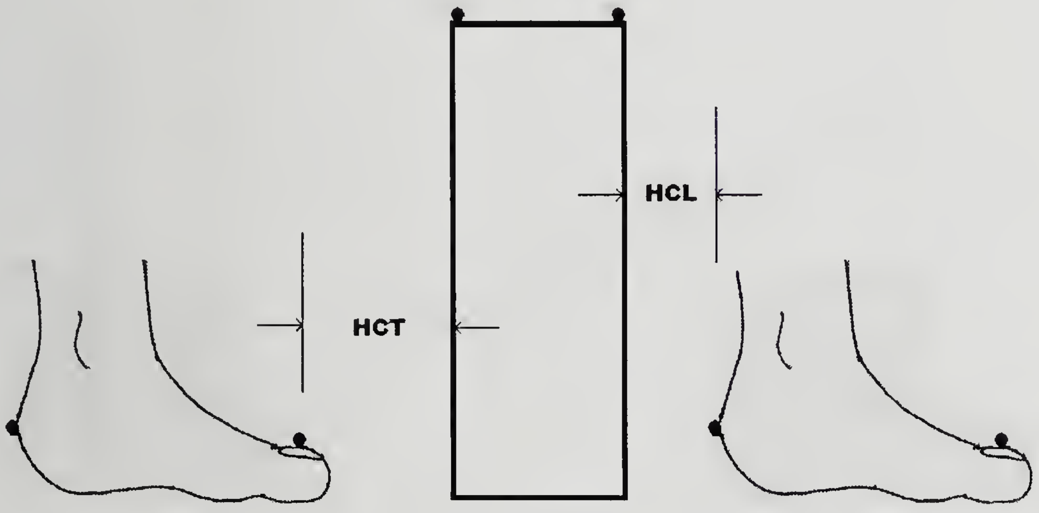

Figure 4.2b. Horizontal clearances with respect to the obstacle of the lead (*HCL*) and the trailing (*HCT*) foot. Clearances were calculated at heel strike of the trailing foot immediately prior to crossing the obstacle, and at heel strike of the lead foot immediately after crossing the obstacle.

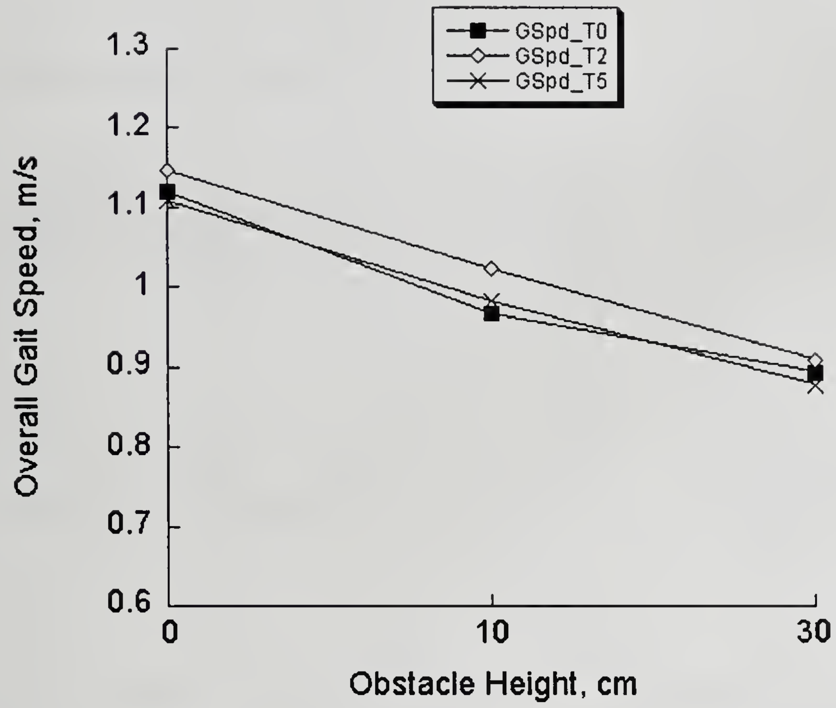

Figure 4.3a. Mean overall gait speed as a function of obstacle height and training month. Gait speed was based on the time to cover a distance of 3.5m.

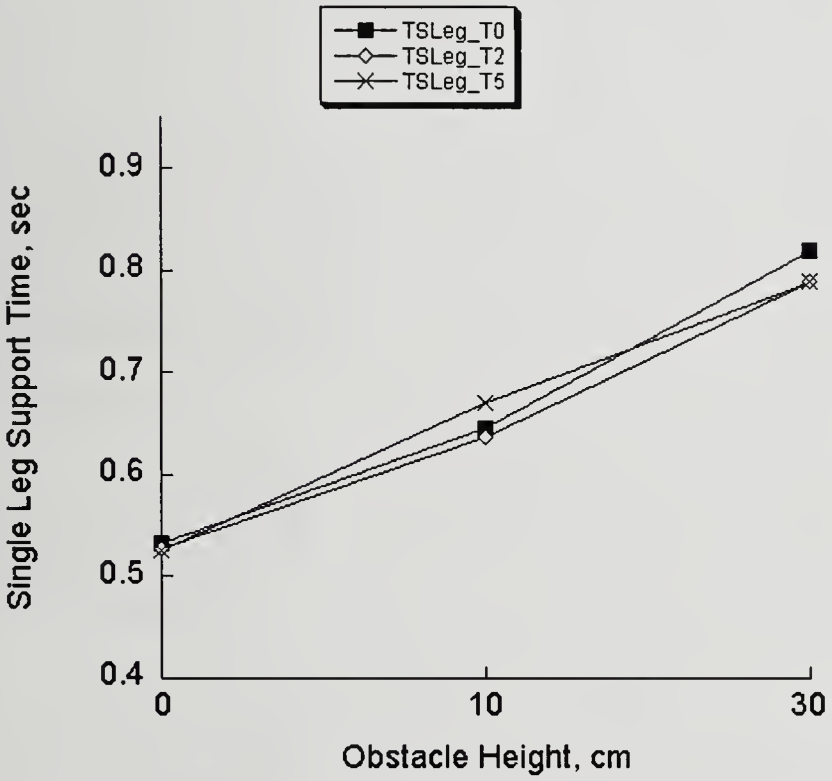

Figure 4.3b. Mean time spent in single leg support for the crossing step. The time was calculated from toe-off just prior to crossing the obstacle to heel strike after crossing the obstacle for the lead foot.

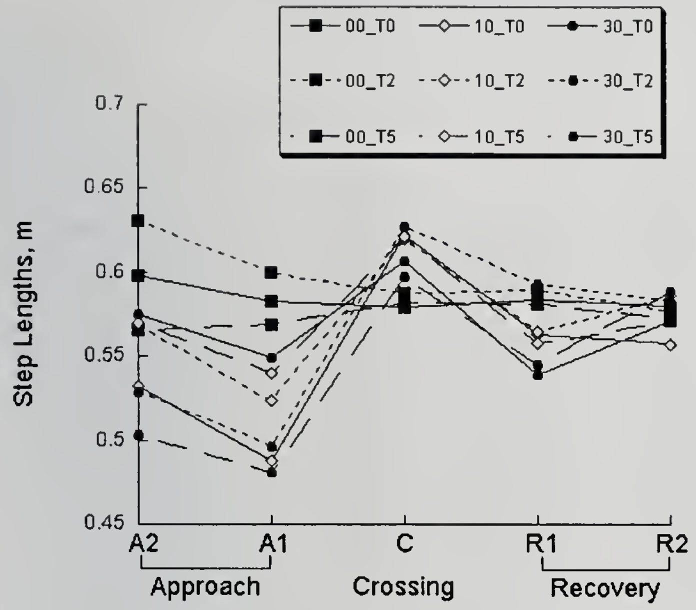

Figure 4.4a. Step length at the five measured step positions as a function of training month and obstacle height. Step length was defined between successive heel strikes.

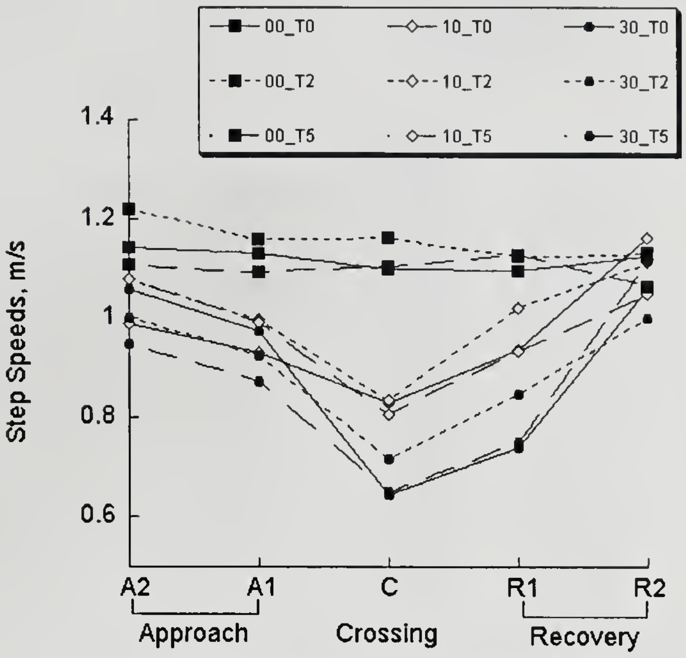

Figure 4.4b. Individual step speed as a function of training month and obstacle height. Step speed was defined as the ratio of the step length to the time interval between heel strikes, for a given position.

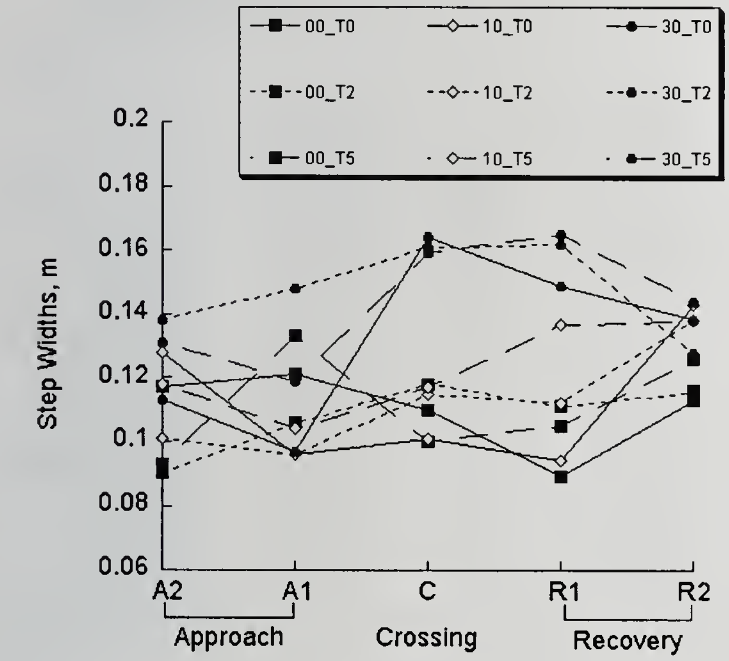

Figure 4.4c. Step width as a function of training month and obstacle height. Step width was defined as the medial-lateral displacement of the heel marker between successive heel strikes.

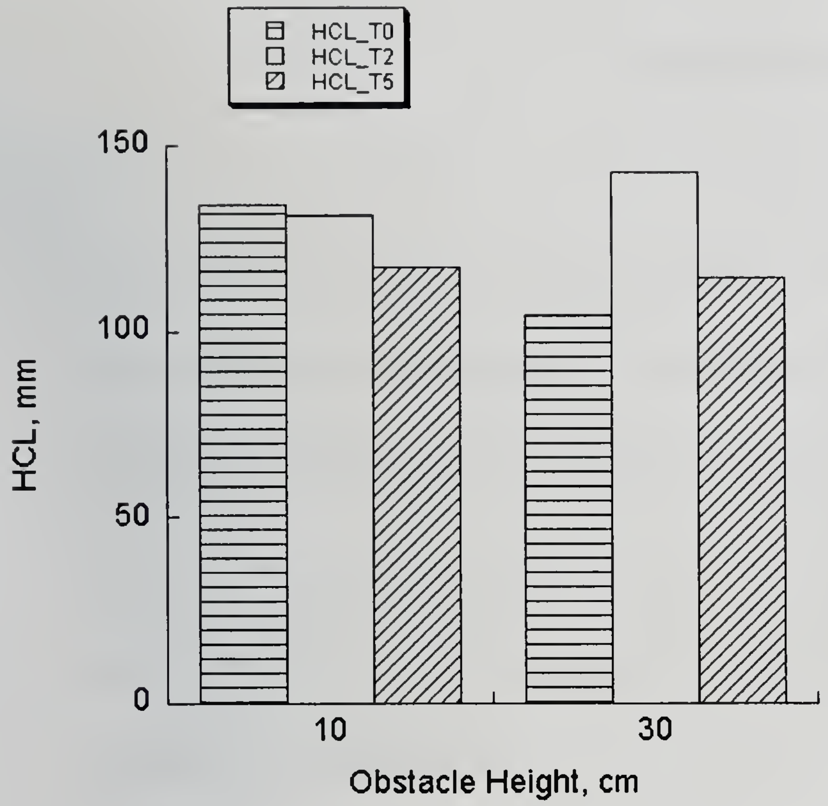

Figure 4.5a. Horizontal clearance between the heel of the lead foot and the back of the obstacle, at heel strike immediately after crossing the obstacle.

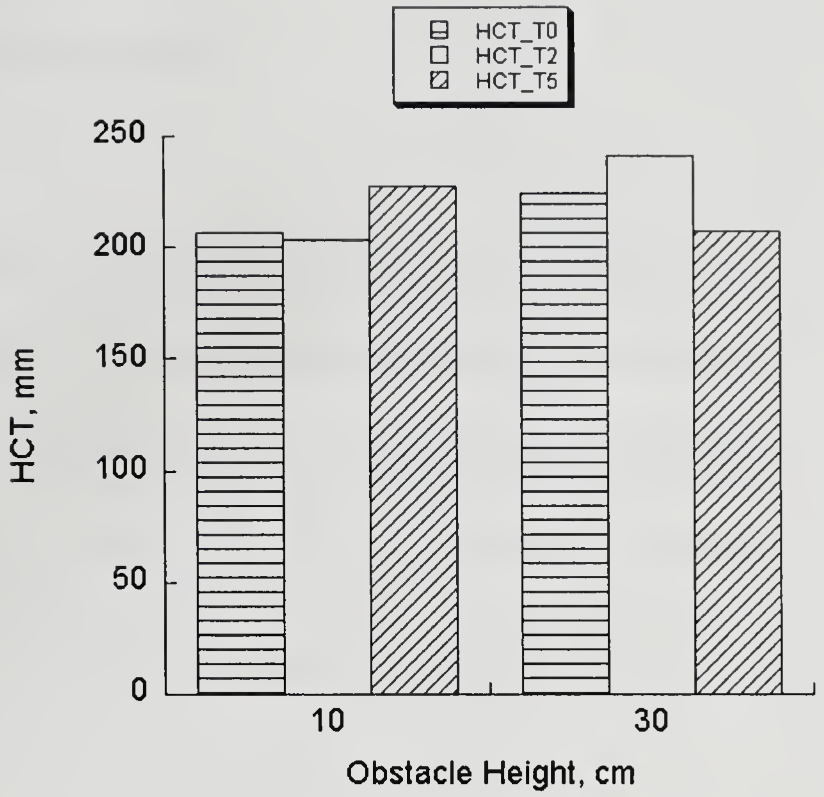

Figure 4.5b. Horizontal clearance between the toe of the trailing foot and the front of the obstacle, at heel strike immediately prior to crossing the obstacle.

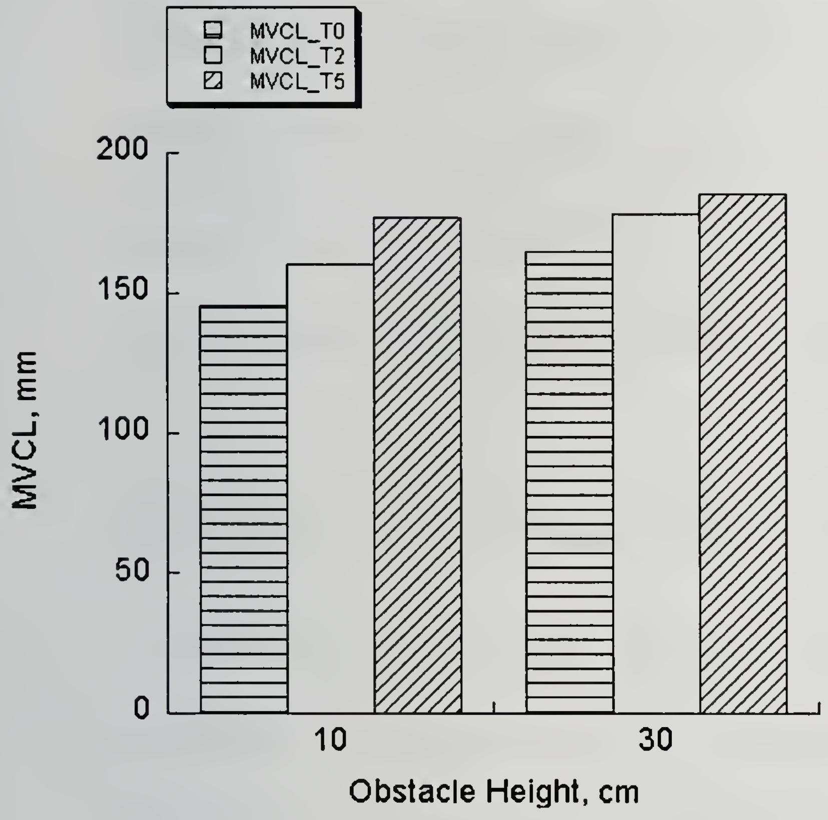

Figure 4.5c. Minimum vertical clearance between the lead foot (toe or heel) and the obstacle (front or back), during the crossing step.

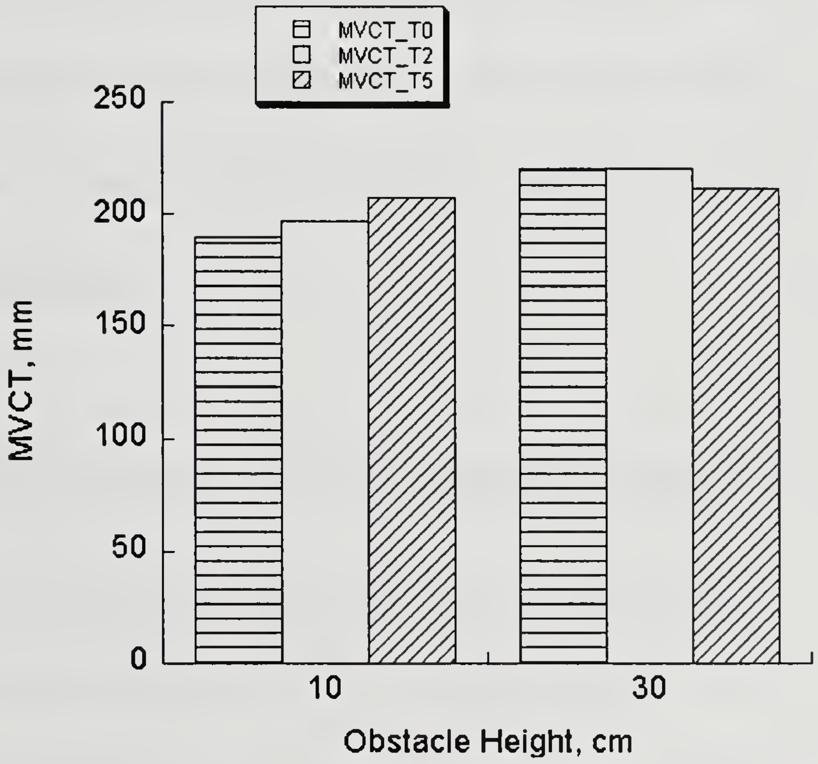

Figure 4.5d. Minimum vertical clearance between the trailing foot (toe or heel) and the obstacle (front or back), during the crossing step.

CHAPTER 5: CONCLUSIONS

No previous research has investigated stance width constrained quiet-standing balance and obstacle crossing strategies as a function of expertise in Tai Chi, and as a function of training in Tai Chi. A cross-sectional study involving fifteen experienced Tai Chi practitioners and their age, gender and activity level matched controls, and a longitudinal study on fourteen elderly adults from the local community enrolled in a Tai Chi training program for a period of five months were performed.

In Chapter 2, we present cross-sectional study where quiet-standing balance was evaluated. Supporting our hypothesis, we found that Tai Chi practitioners adopted a wide stance width when asked to take their normal comfortable stance. When subjects from both groups were controlled to different stance positions, no significant differences were found in postural sway response between the groups, which was also in support of previous findings. The major results obtained from this study showed that postural sway significantly increased, especially in the medial-lateral direction, when stance width was constrained.

In Chapter 3, we investigated obstacle crossing strategies used by the cross-sectional population. We found that the strategies adopted by the Tai Chi practitioners when presented with obstacles of different heights in the path of their normal gait revealed that they used more cautious strategies in modifying their stride characteristics. In comparison to the controls, they walked with slower individual step speeds, and hence with a slower overall average speed, shorter steps, and longer time in single leg support when crossing the obstacles. Interestingly, Tai Chi

practitioners also appeared to place their trailing foot closer to the obstacle prior to crossing it, and the lead foot closer to the obstacle after crossing it when compared to the controls. As observed from previous research, the above strategy forced them to produce smaller vertical clearances between the obstacle and both the lead and trailing feet. We conclude that further investigation is required of the lower extremity kinematics to identify the relative contributions of the various joints in producing the observed clearances. Variability in the clearances also needs to be determined.

In the longitudinal study on elderly adults presented in Chapter 4, kinematic analysis performed on the subjects at the beginning of the training, after two months and after five months of training revealed that, overall, the subjects were able to generate greater vertical clearance on the leading foot with Tai Chi training. Subjects were also able to adjust their gait from normal walking when confronted with obstacles of varying height in their path. This latter finding is consistent with our previous research on obstacle crossing (Chapter 3). Further analysis is required to identify specific individuals who were able to significantly change their obstacle crossing strategy with Tai Chi training.

The studies gave us a first insight on how obstacle crossing strategy gets modified with exposure to Tai Chi. Based on the results obtained from the studies, we recommend future research to investigate the biomechanical changes associated with these strategies. The research would be beneficial in identifying the aspects of Tai Chi which make it a constructive intervention program for the elderly population.

UNIVERSITY OF ILLINOIS-URBANA
3 0112 061042419